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EDDY CURRENT SCANNING REPORT

FNAL-3RDHARMONIC CAVITY #2

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Aknowledgment:

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1 INTRODUCTION

As part of Fermilab's effort to develop 3rd harmonic cavities for the A0 photo-injector test facility, the niobium blanks as delivered by Wah-Chang were scanned with the eddy-current technique to reveal foreign inclusions or other sub-surface defects. The results of the scanning procedure are reported in this note. Also included are the results of a visual inspection of the surface using a magnifying glass. The report concludes with recommendation regarding the use of the blanks for subsequent cavity fabrication.

Fermilab recently commissioned a scanner (Figure 1), on loan from SNS. Some recent upgrades of the scanner hardware include a vertical micrometer slide (Figure 2) that simplifies the process of positioning the eddy current probe with a minimum distance to the sample surface. Electrical continuity measurements between the sample-holder and the probe (fully retracted, while turn-table is spinning) were used as a technique to determine the minimum probe to sample distance.

To accommodate the smaller samples for the Fermilab 3.9 GHz cavity program on the SNS scanner, which was designed to hold much larger Nb sheets, a special sample-holder had to be fabricated. It consists of an aluminum base-plate with a Nb ring affixed to it. The Nb ring brings the sample-holder up to the level of the sample. The base-plate diameter is large enough to cover the inner of the two O-rings on the turntable. The suction holes between the inner and outer O-rings are

Figure 1: SNS eddy current scanner at Fermilab. 1) turntable with sample, 2) eddy-current tester, 3) main-power switch, 4) air receiver.

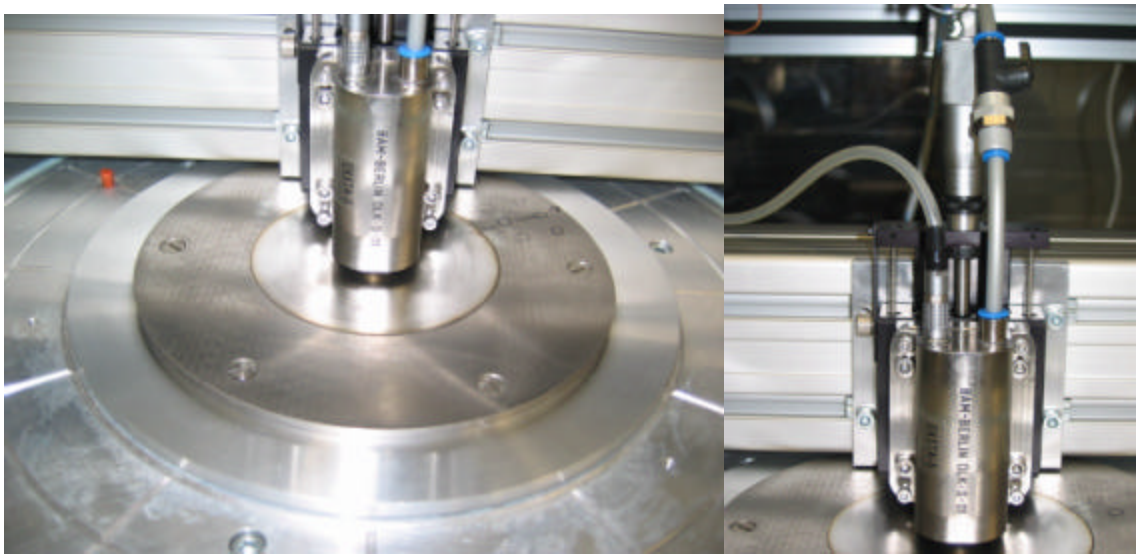


Figure 2: Left: Sample-holder with sample and eddy-current probe. Right: Eddy current probe with micrometer slide, compressed air supply tube and signal cable.

blocked with rubber plugs (one of them can be seen in Figure 2). The aluminum base-plate transfers the suction to the sample placed on it. For sealing purposes the sample sits on an O-ring, which compresses as the sample is pulled down by the suction. Figure 3 shows the sample-holder for the 3rd harmonic discs, which have a 3.93" diameter and a ~0.011" thickness. A more thorough description of the scanner and the sample-holder can be found in the internal note TD-04-029.

In the particular case of the discs discussed here, the scanning at Fermilab consisted in repeating the scanning done previously at DESY by A. Brinkmann. The DESY scanner can be considered as the bench-mark facility since the development of the technology evolved around it. The bench-marking with the DESY scanning results allows us to gauge the quality of our scans before venturing into qualifying new material. The comparison of the results obtained with the DESY and SNS/FNAL systems revealed that the SNS/FNAL scanner can resolve the defects detected with the DESY scanner. The sensitivity of the SNS/FNAL device is, however, somewhat smaller. The upgrades of the scanner mentioned above have been implemented with the goal to enhance the SNS/FNAL scanner sensitivity. **Figure 4** shows such a comparison for disc 22 (side 2), which had clearly visible defects in both cases. The defects consisted of ~100 μm deep holes at the surface, which were also visible with the naked eye. Note that the scanner is most sensitive to sub-surface defects since the high frequency channel (channel 2) could not be exploited (in both the DESY and FNAL cases).

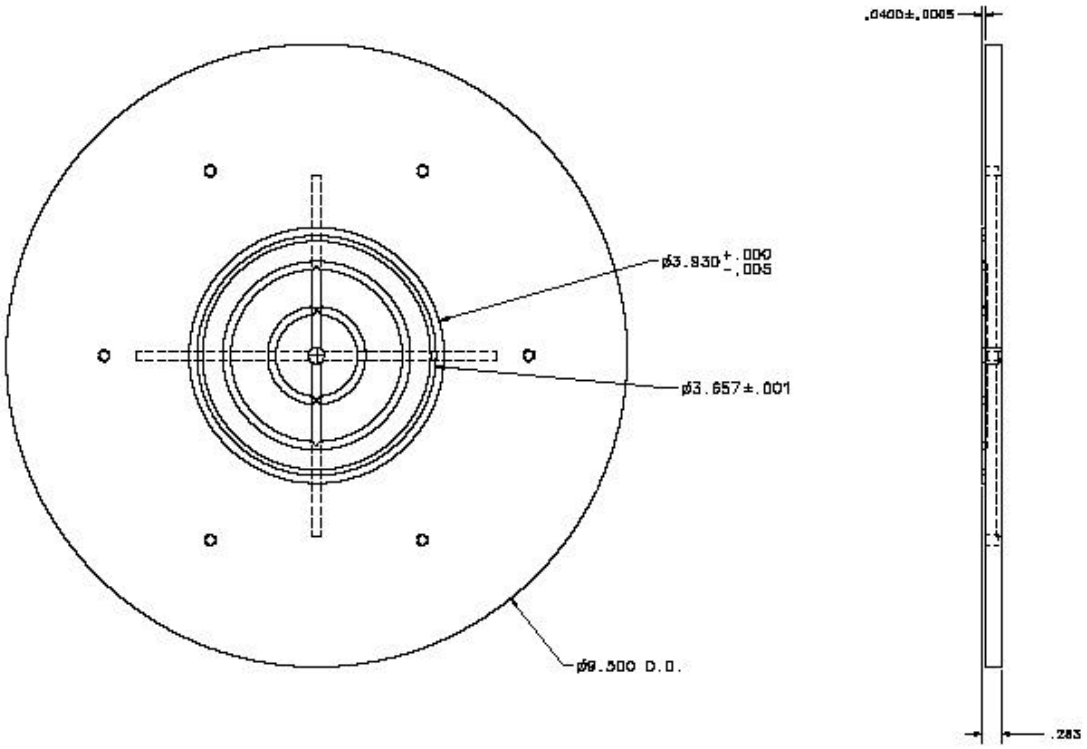


Figure 3: Aluminum base of the sample-holder for the 3rd harmonic cavity discs at Fermilab. Given dimensions are in inches. The 3rd harmonic discs have a 2.8 mm (0.011") thickness and a diameter of 3.93". Not shown is the outer Nb ring (ID~4.63"). The step-height of the center pedestal is 0.04". The design is such that the upper surface of the disc is flush with the upper surface of the Nb ring.

The following scanning procedure was applied to each sample.

1) The system was switched on at least one hour before testing. Disc 22_2[1] was run first to determine whether the scanner is operating correctly.
2) The sample was inspected under the magnifying glass and any observations concerning the condition of the surface (scratches, etch-pits, de-colorations, …etc) were noted. Samples were always handled with gloves.
4) After mounting the sample the probe was moved over the center of the sample and brought down, followed by an activation of the turntable. The micro-slide was then brought up or down, such that there was just not electrical continuity between sample-holder and probe-holder.

[1] 3rd harmonic – batch 1 – disc 22- side 2 is the disc showing the clearest evidence of defects in the DESY and FNAL scans (see **Figure 4**).

5) The phase was set such as de-couple defects (y-signal) from disc thickness variations (x-signal) and sometimes the amplifier gains were varied as well as the low-pass filter settings.
6) The measurement was launched, with the files named according to the following convention: project_batch#_disc#_disc-side_#ofrun).
7) The measurement was continuously observed and the probe pulled up with the micro-slide whenever touching between the sample and probe occurred (these measurements were then repeated with the new height setting.

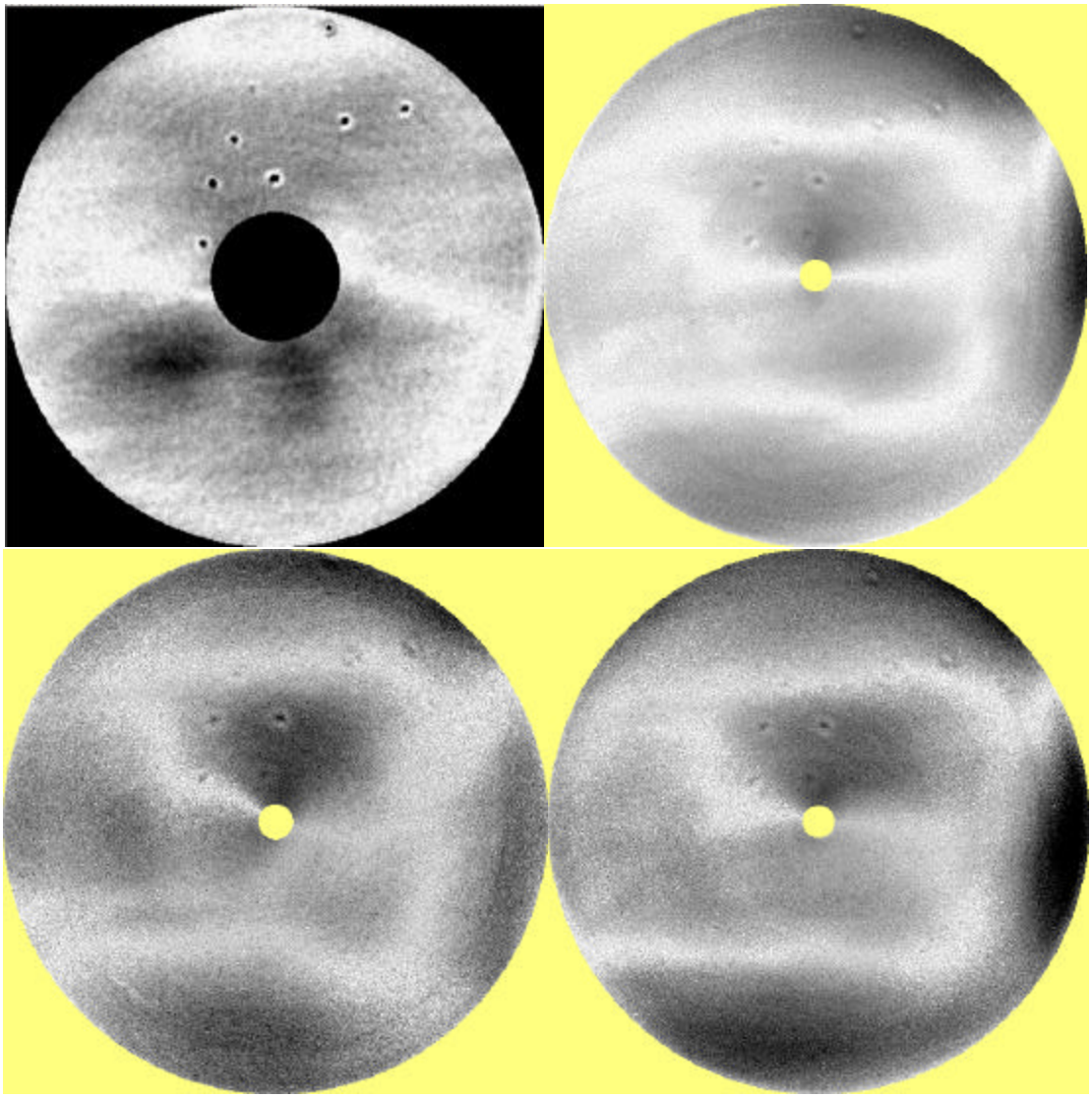


Figure 4: Example of eddy current scans performed on a niobium disc for Fermilab's 3rd harmonic cavity with the DESY scanner (top left) and SNS/FNAL scanner (top right and left & right bottom).

8) The measurement result was saved, printed and inspected. In many cases several measurements were performed per disc. This is especially true for the samples which had shown defects in the DESY scans. Scanner parameters varied were (in the order of importance): probe top sample distance, gains and low-pass settings;

The typical scanner settings for the SNS/FNAL and DESY scans are summarized in Table 1. The data shown in the following chapters are all of channel 1 (y-signal). Channel 2 was usually operated with 1.2 MHz (1 kΩ probe adjust). Since the channel 2 data could not unambiguously be interpreted in both the FNAL and DESY cases, they were not further analyzed here. The only major differences in the settings of the two devices are that the turntable is rotating faster in the case of the SNS/FNAL scanner, because it was built to scan much larger discs than the DESY scanner.

Special measurements were performed in some cases to determine how much etching is needed to remove the observed defects. These measurements are reported in a special section at the end of this report.

Table 1: Main menu settings of the Rohmann ELOTEST. *In some instances a pre-amplifier gain of 30 was used.

Parameter	Channel 1 – SNS/FNAL	Channel 1 - DESY
Frequency	170 kHz	170 kHz
Probe Adjust	50 Ohm	50 Ohm
Probe Current	333 mA	333 mA
Phase	207-208 deg	356 deg
Pre-amplifier	20(30*) dB	20 dB
Total gain (x/y)	42-48/62-68 dB	44/64 dB
X/Y spread	0/20 dB	0/20 dB
Highpass filter	static	static
Lowpass filter	0.5-2 kHz	0.5 kHz
BW limit	off	off
Point spacing	50 μm	200 μm
Track spacing	< 30 μm (0.225°)?	200 μm
Tangential speed	< 425 mm/s ?	10.28 mm/s

2 VISUAL INSPECTION REPORT

Table 2 contains the results of the visual inspection of the 27 discs of the second half of the first batch of material for the FNAL third harmonic cavities. The visual inspection was performed using a simple magnifying glass. The indicated numbers are approximate angle coordinates on the discs, where the angle is counted clockwise from the 12:00 position (line-mark) on the disc. OR stands for “outer rim”, that is the ~5 mm band at the outer rim of the disc. It is to be assumed that this area will be removed during subsequent production steps. MR stands for the ring in the middle, which will also be stamped out. HR stands for “half radius” and scratches, dents and pits in this area are more serious. This area will be used in the subsequent cavities. Most of the discs have very faint “rolling marks” and oxidation along the edge as a result of the EDM cutting. These features have therefore not been mentioned explicitly in the table below.

Table 2: Optical inspection report for batch 1 3rd harmonic niobium (part 2).

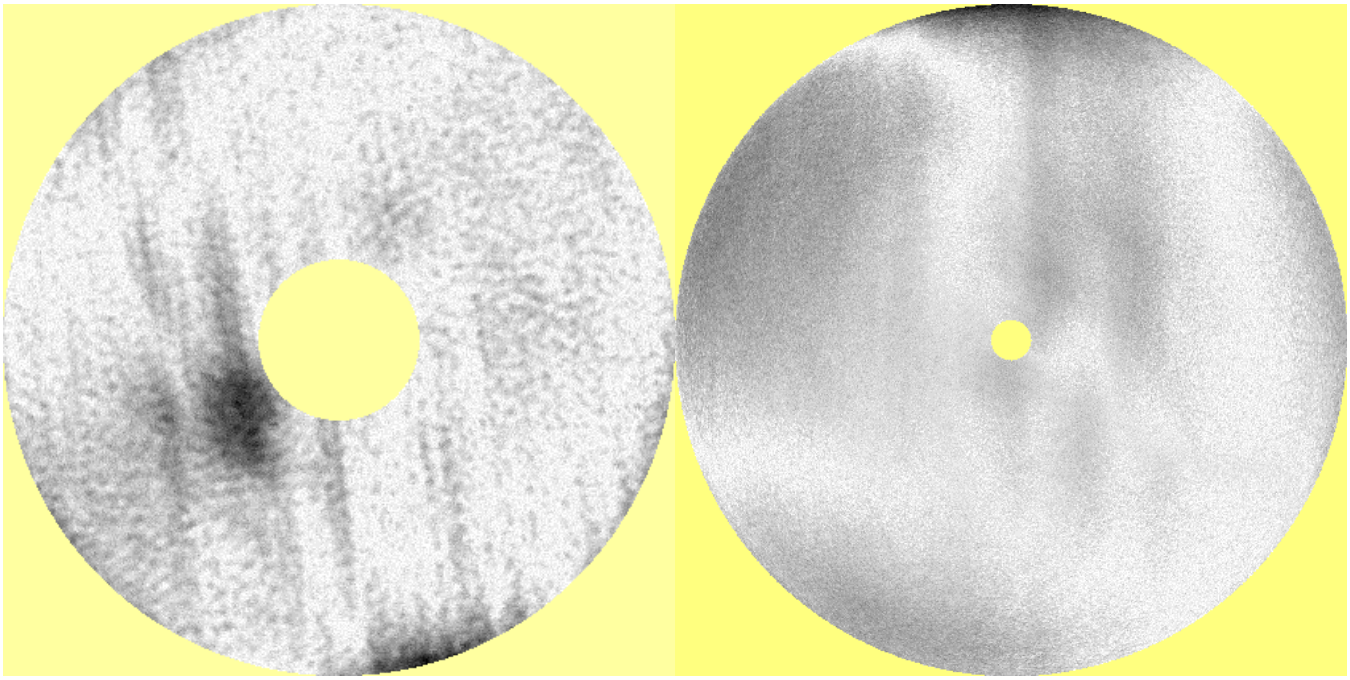
#	disc	comment
1	1	S1: ok S2: scratch 0 MR (**defect 120 HR in DESY scan**) Large thickness variation
2	2	S1: ok S2: scratch 0 MR
3	3	S1: ok, strong oxidation from EDM cutting S2: scratch 0 MR thick edge 250 OR
4	4	S1: nick 90 OR S2: ok
5	5	S1: ok S2: small pit 130 OR, more than usual oxidation from EDM cutting OR
6	6	S1: scratch 0 MR, oxidation OR S2: ok
7	7	S1: ok S2: scratch 0 MR
8	8	S1: pits 70 OR, scratch 180 MR, oxidation from EDM cutting OR, (**marked by DESY**) S2: scratches 0 & 180 MR
9	9	S1: pit 90 OR S2: **scratches 0 HR & 120 HR-OR**
10	10	S1: dent 260 OR, speck 310 HR S2: pit 310 OR
11	11	S1: **pit 20 HR** S2: **scratch 120 OR-HR**
12	12	S1: **surface scratches** S2: black speck 210 OR (**marked by DESY**)
13	13	S1: scratches, **dent 180 OR-HR** S2: scratches 180-210 OR
14	14	S1: **dent 200 HR**, dent 25 OR S2: **pits 0-90 & 260-360 HR, scratches HR-OR** (**13 defects 285 HR in DESY scan**)
15	15	S1: specks 10-30 OR S2: scratch 0 MR
16	17	S1: **pits 310-360 & 150 HR, scratches** (**marked by DESY**) S2: scratch 0 MR, specks 120-140 HR
17	19	S1: pit 75 OR, scratch 300 OR S2: **scratches, dent 30 HR** (**defect 12 HR in DESY scan**)
18	20	S1: **scratch 355 HR**, scratch 210-270 OR S2: scratch 120 OR, oxidation from EDM cutting
19	21	S1: **scratch 90 MR-HR**, pit 40 OR, scratch 355 OR S2: **scratch 100-130 HR**, speck 270 HR

#	disc	comment
20	24	S1: **scratch HR 250-260** S2: **scratches 180-220 HR-OR**, scratch 10 MR
21	27	S1: ok S2: scratch 140 HR, pits 170-300, (**13 defects 180 & 270 HR in DESY scan**)
22	32	S1: **ding 40 OR-HR** S2: **scratches, dings and specks 170-200 HR (defect 180 HR in DESY scan)**
23	33	S1: **scratch 30&200 HR** S2: ding 290 OR, **bump 0.1215"** (rest of disc 0.1180") **disc diameter is very irregular**
24	42	S1: **pit 140 HR** S2: **scratch 290 HR**
25	47	S1: **scratches HR, ding 75 HR, pits 290 HR (defect 75 HR in DESY scan)** S2: ok
26	51	S1: pits all over HR (**many defects 180 & 270 HR in DESY scan)** S2: scratch MR

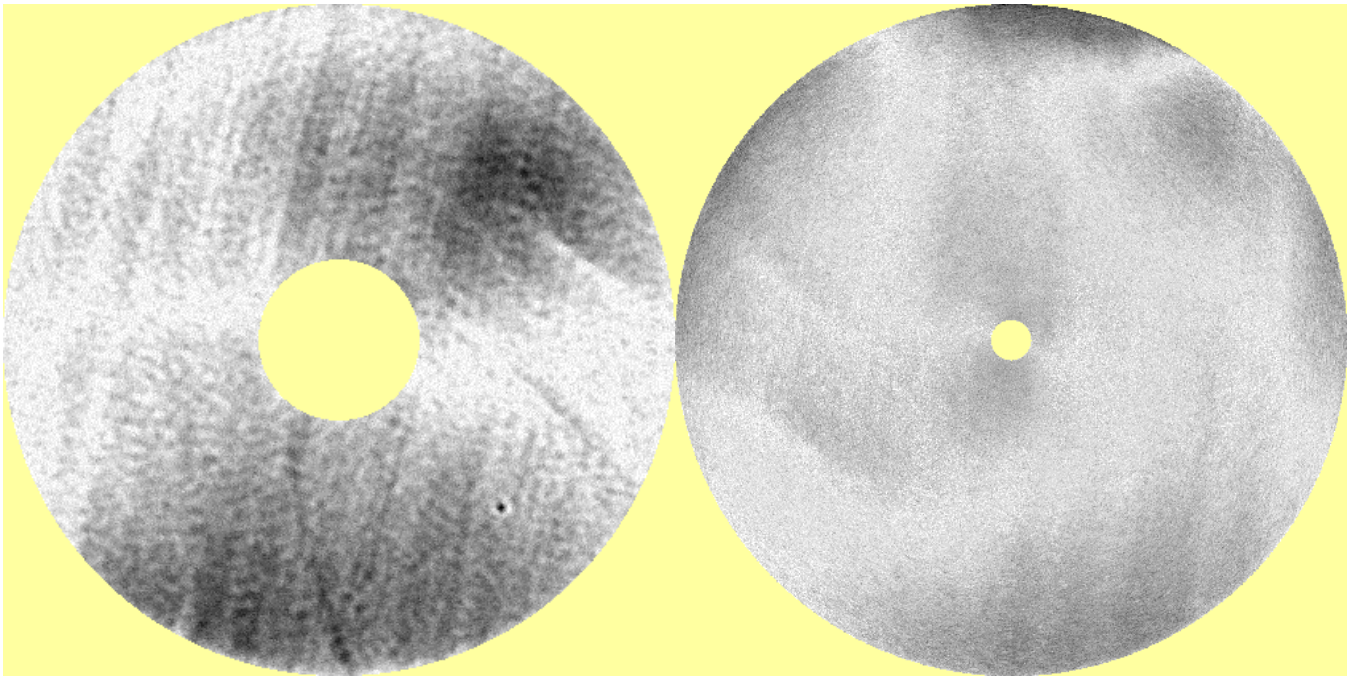
3 COMPARISON OF SCANNING RESULTS

The following shows a comparison of the eddy current scans performed on 26 discs of the first batch of the 3rd harmonic blanks performed with the DESY and the SNS/FNAL scanner. Since the comparison for the case of the "calibration disc" # 22 was performed in **Figure 4**, it is not repeated here. The main purpose of this comparison was to check the sensitivity and resolution of the SNS/FNAL scanner. Of particular interest are the discs, which were shown to have defects in the DESY scans. These are the discs-sides:

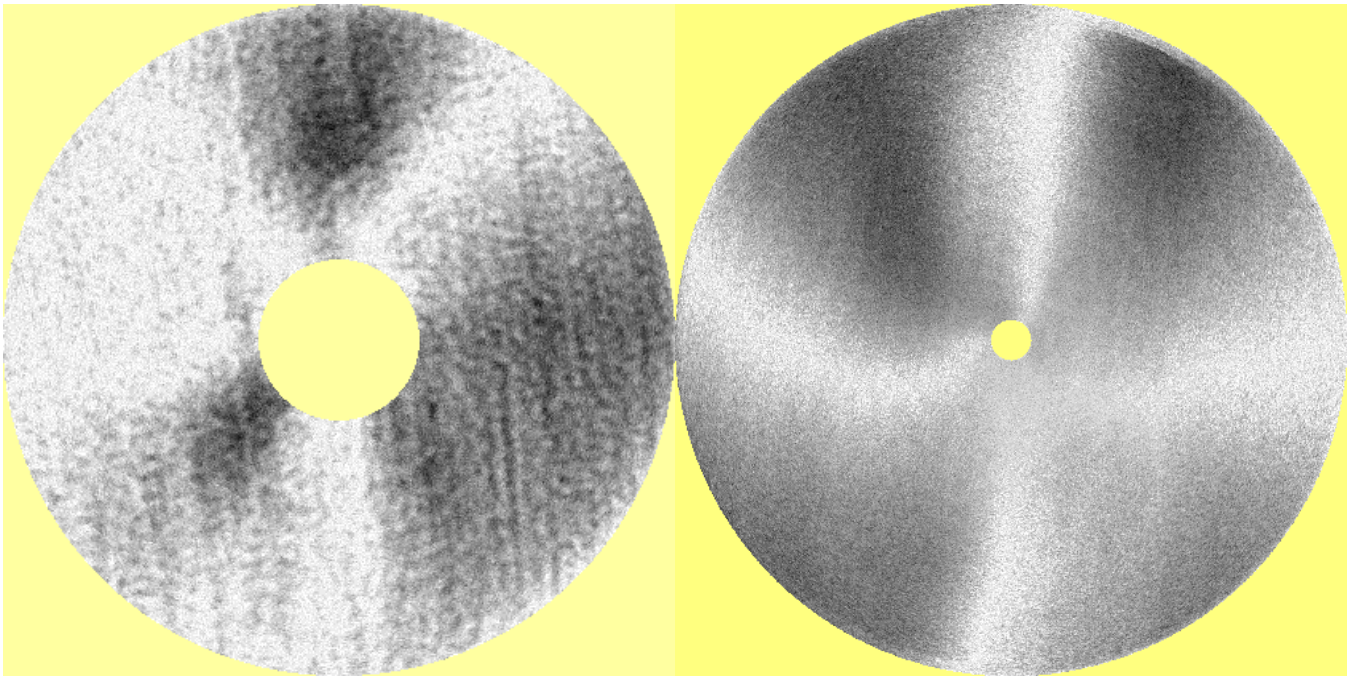
1-2, **8-1**, **12-2**, **14-2**, **17-1**, **19-2**, **27-2**, **32-2**, **47-1**, and **51-1**.



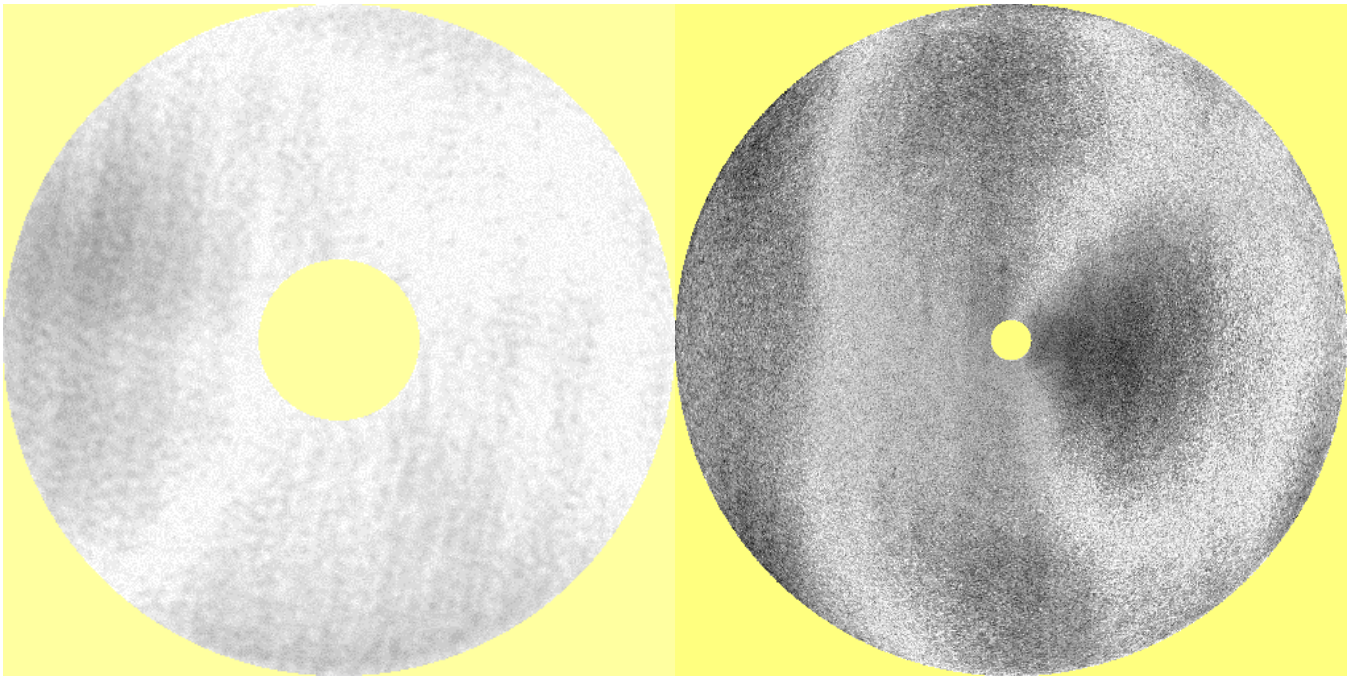
Disc 1 – side 1: DESY (left), SNS/FNAL (right);



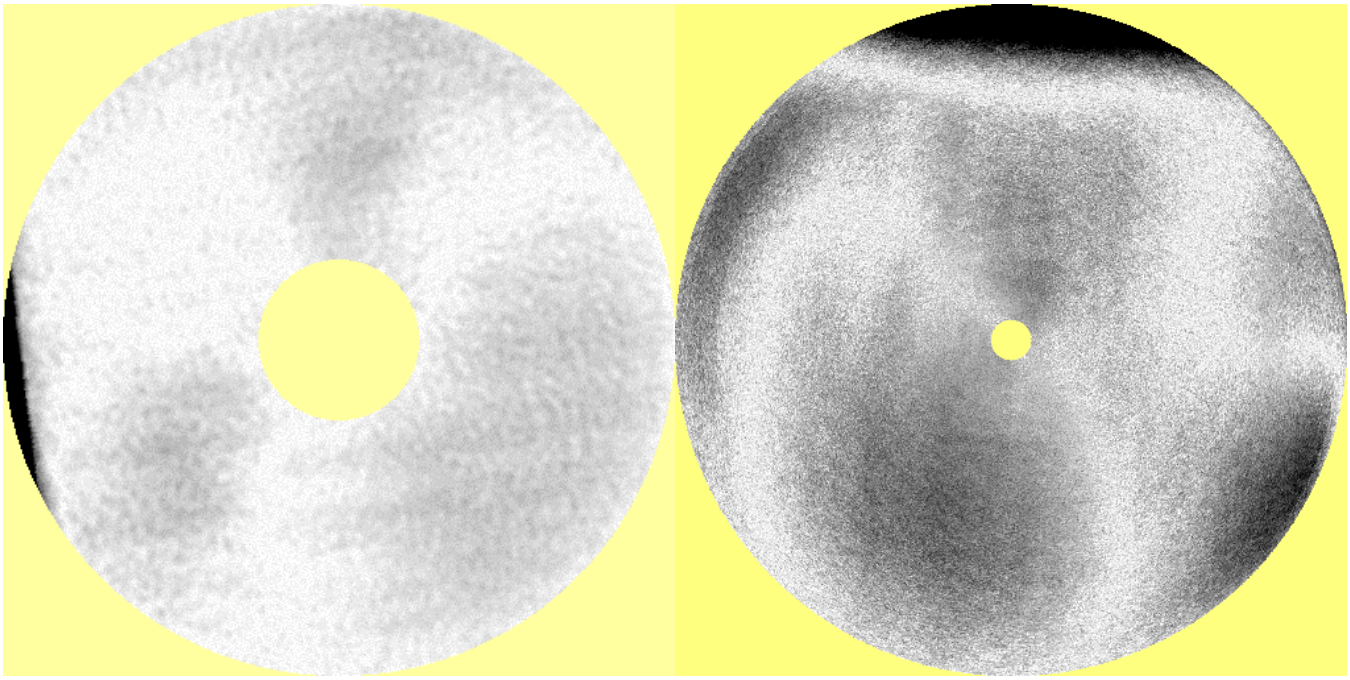
Disc 1 – side 2: DESY (left), SNS/FNAL (right), defect found in DESY scan;



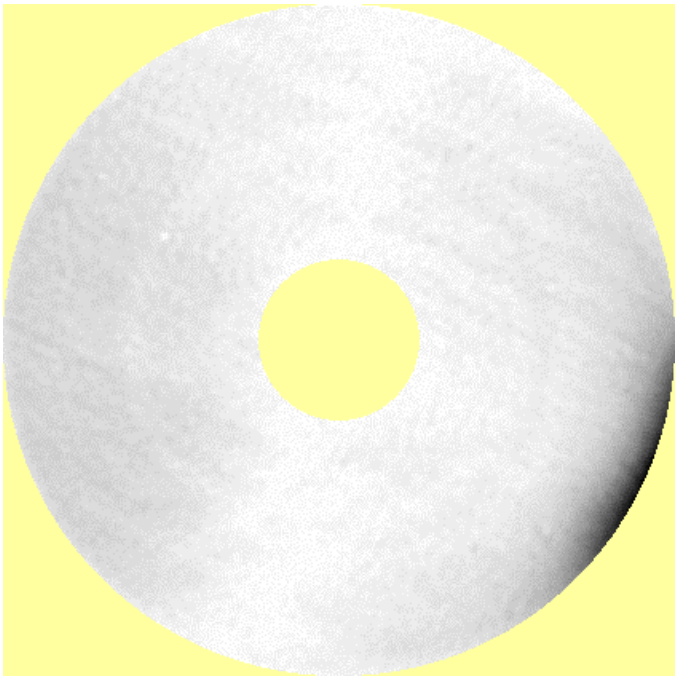
Disc 2 – side 1: DESY (left), SNS/FNAL (right);



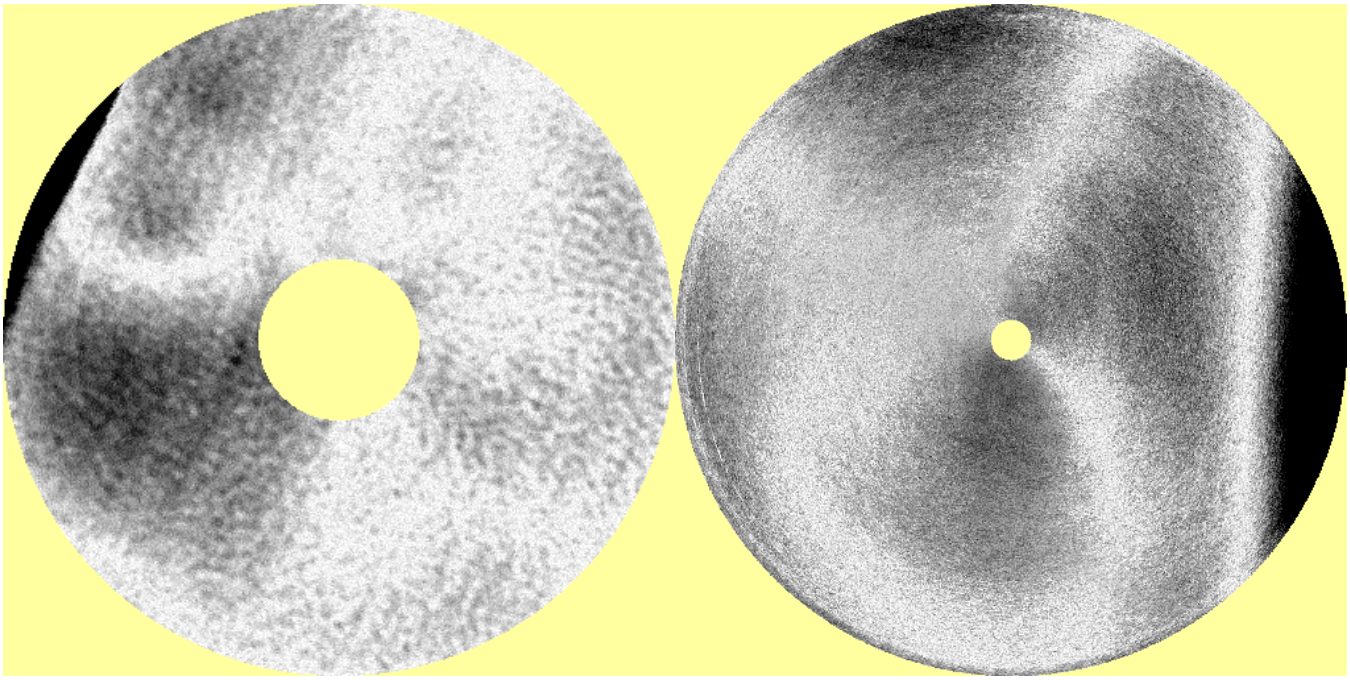
Disc 2 – side 2: DESY (left), SNS/FNAL (right);



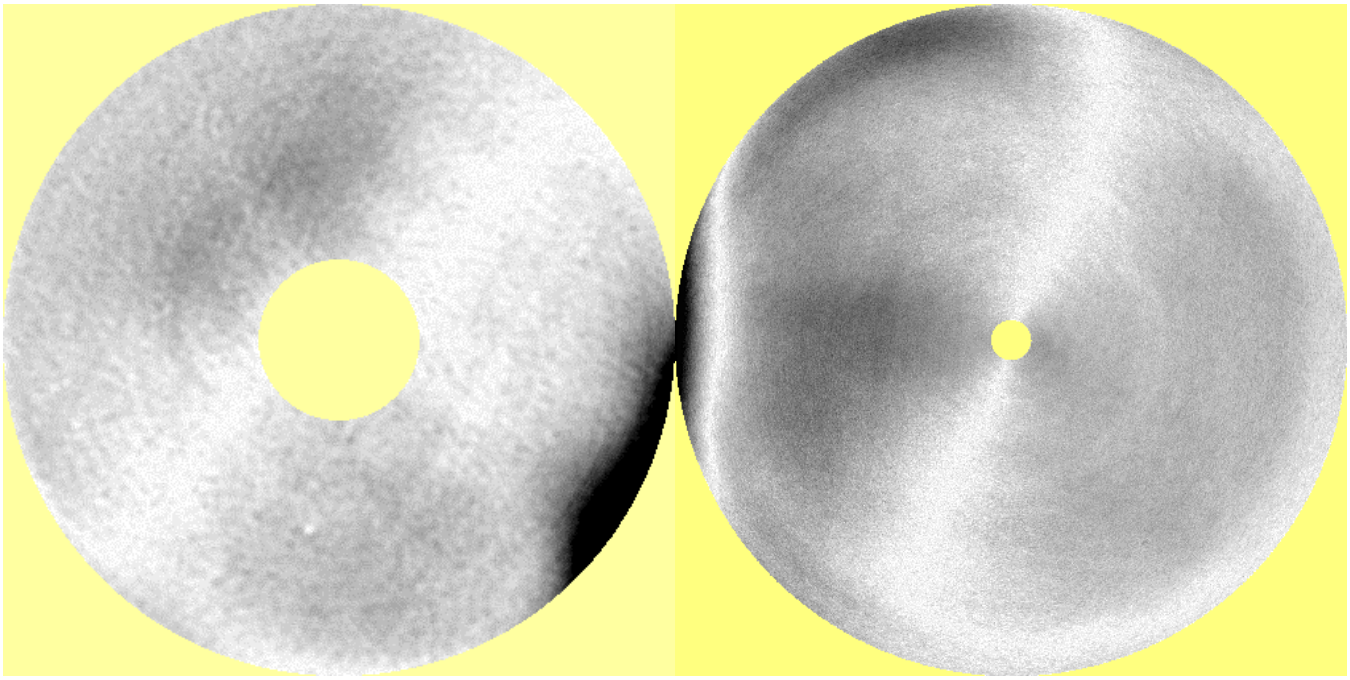
Disc 3 – side 1: DESY (left), SNS/FNAL (right); disc was rotated by ~90 degrees in FNAL scanner in order to fit into sample-holder (major difficulties to remove disc from sample-holder ensued);



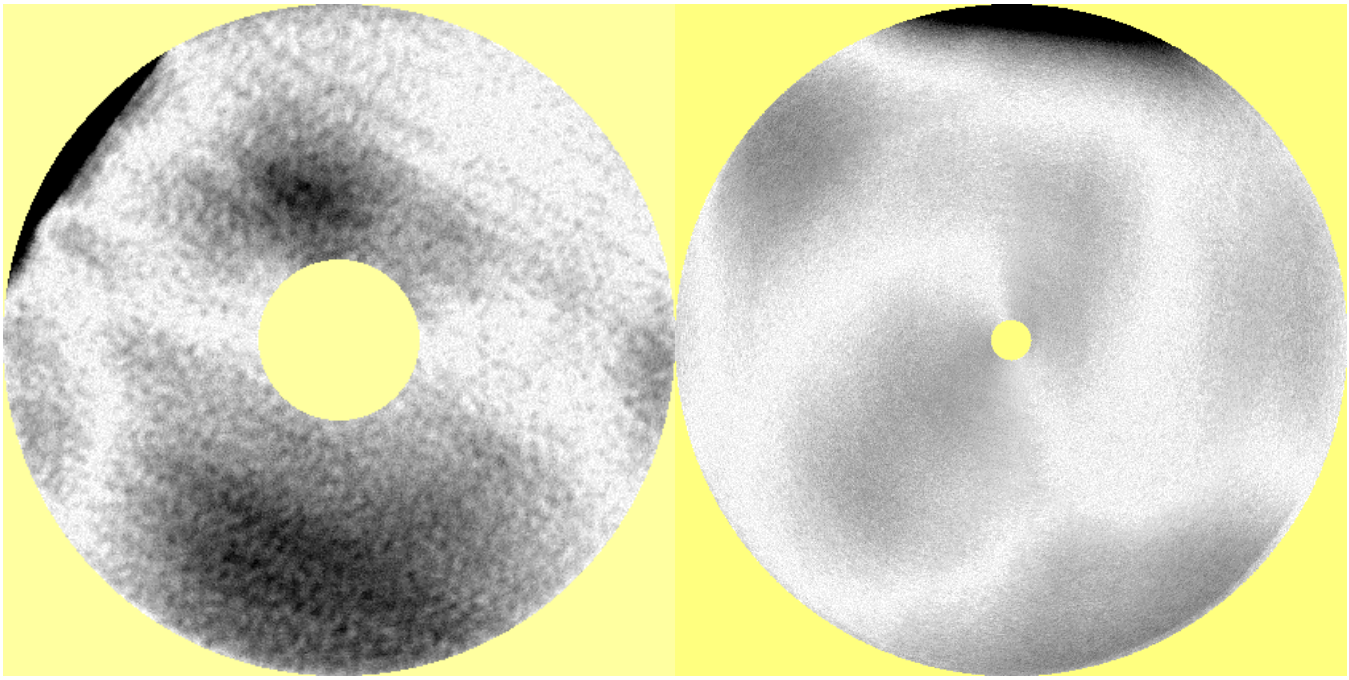
Disc 3 – side 2: DESY (left), disc could not be fit into SNS/FNAL scanner;



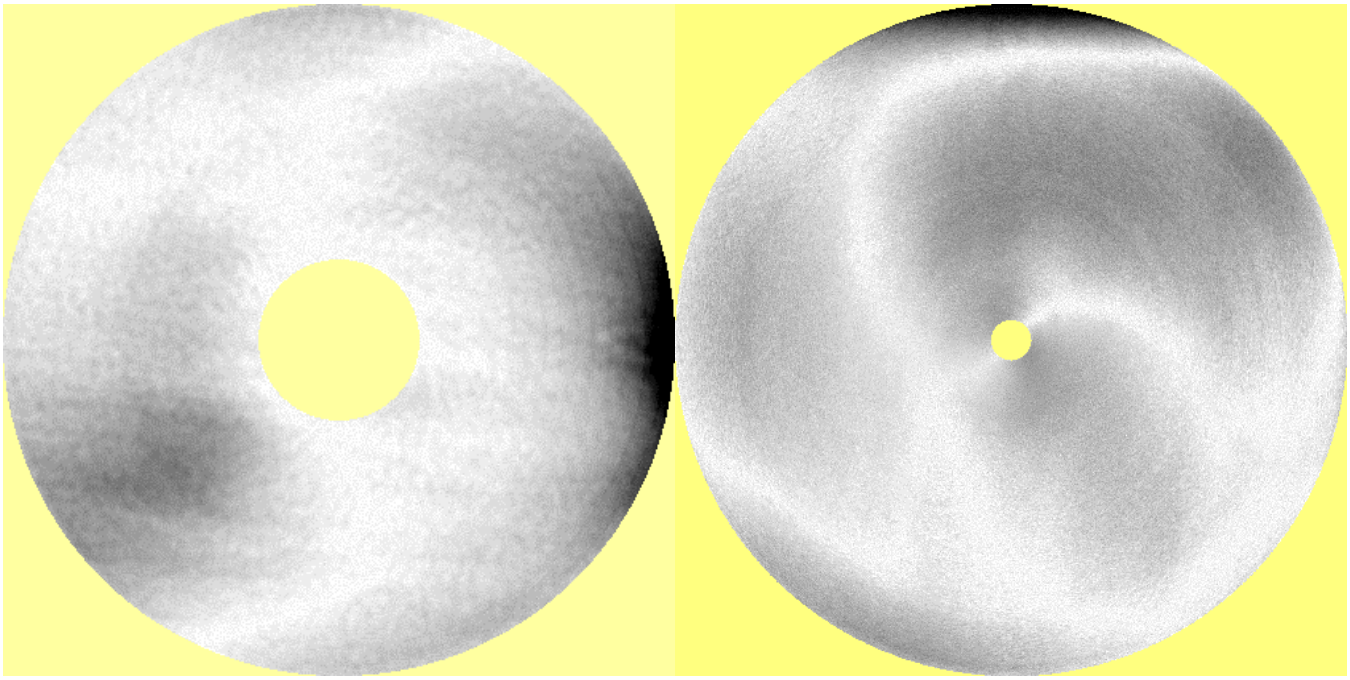
Disc 4 – side 1: DESY (left), SNS/FNAL (right);



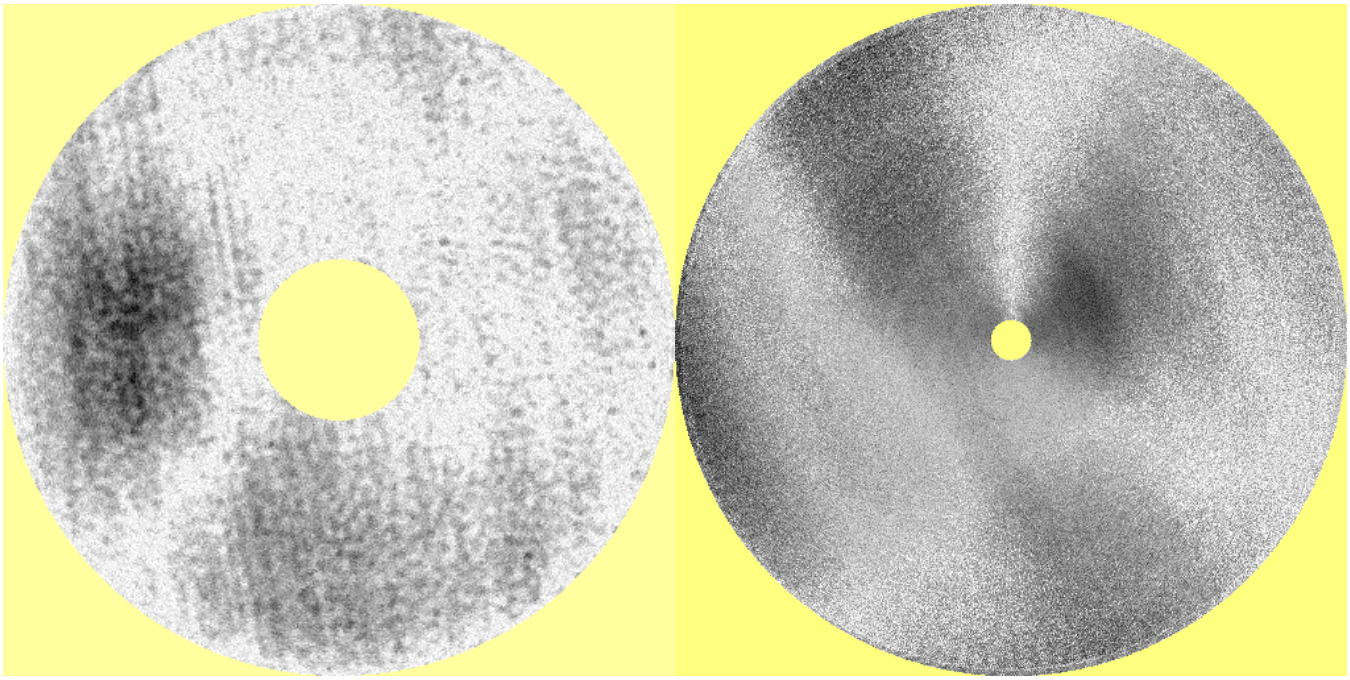
Disc 4 – side 2: DESY (left), SNS/FNAL (right);



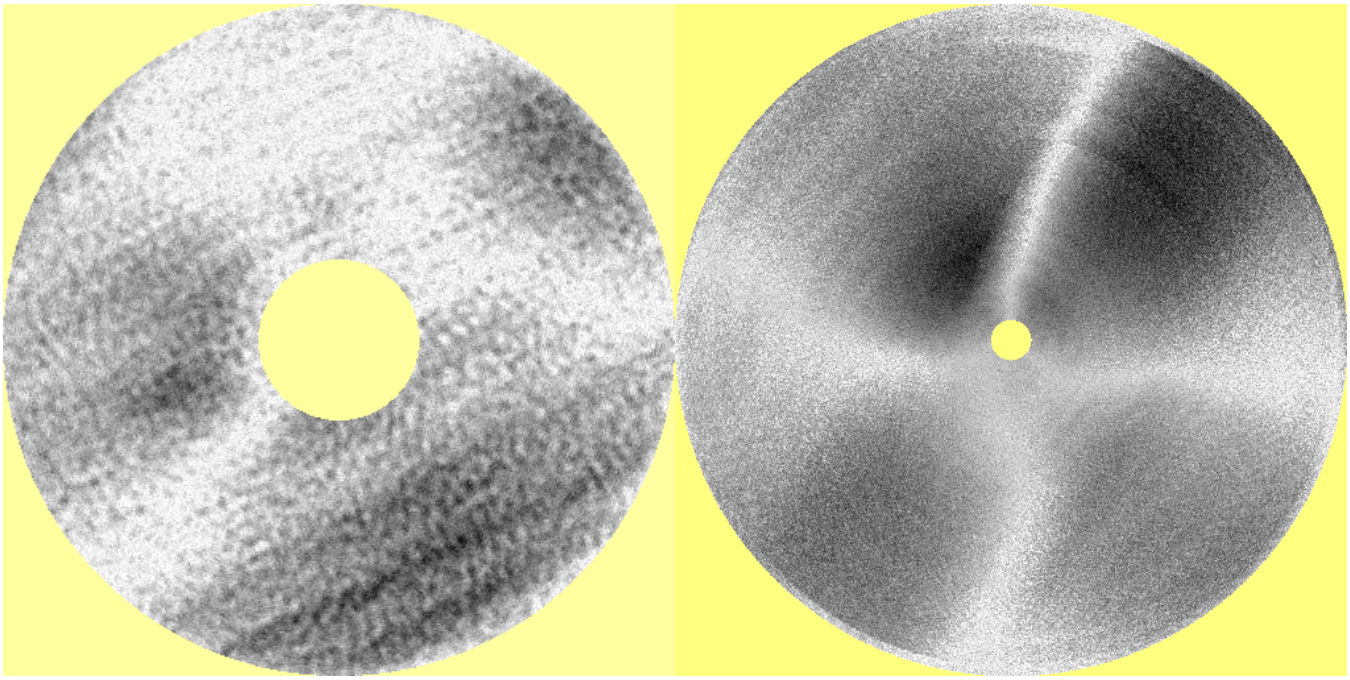
Disc 5 – side 1: DESY (left), SNS/FNAL (right), discs were not oriented the same because direction marks were missing;



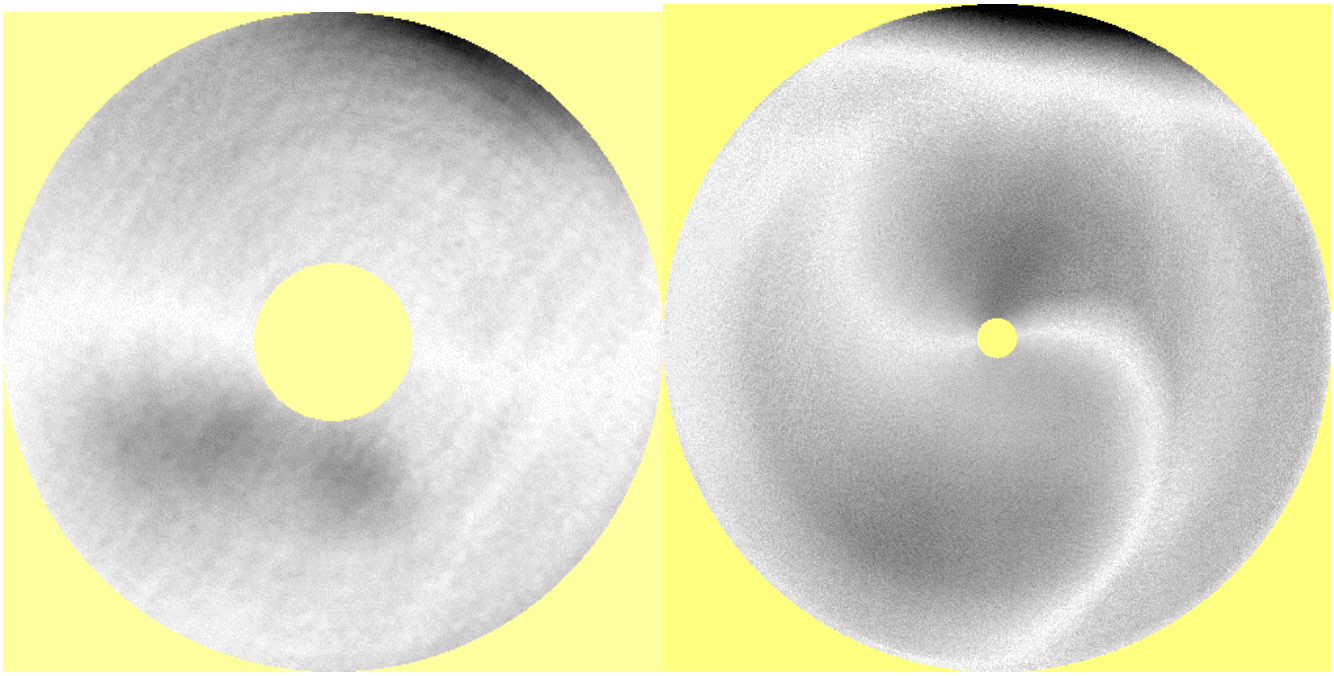
Disc 5 – side 2: DESY (left), SNS/FNAL (right), discs were not oriented the same because direction marks were missing;



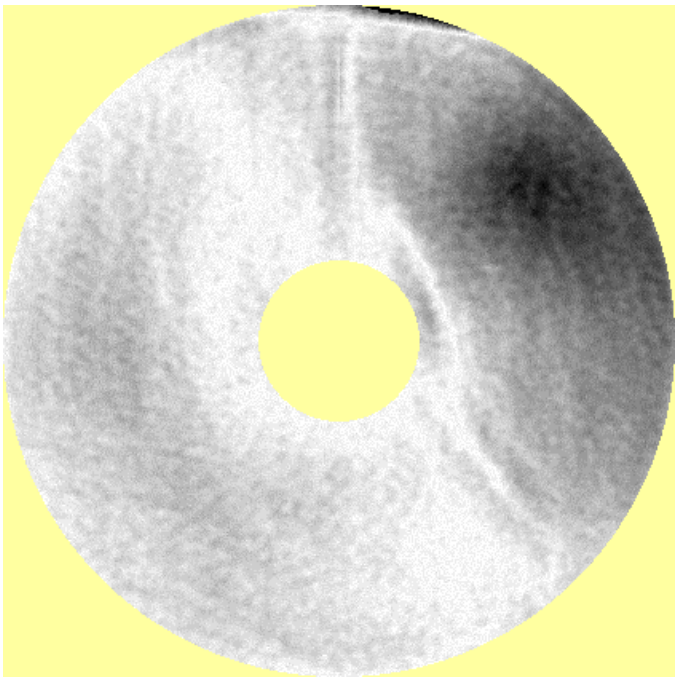
Disc 6 – side 1: DESY (left), SNS/FNAL (right);



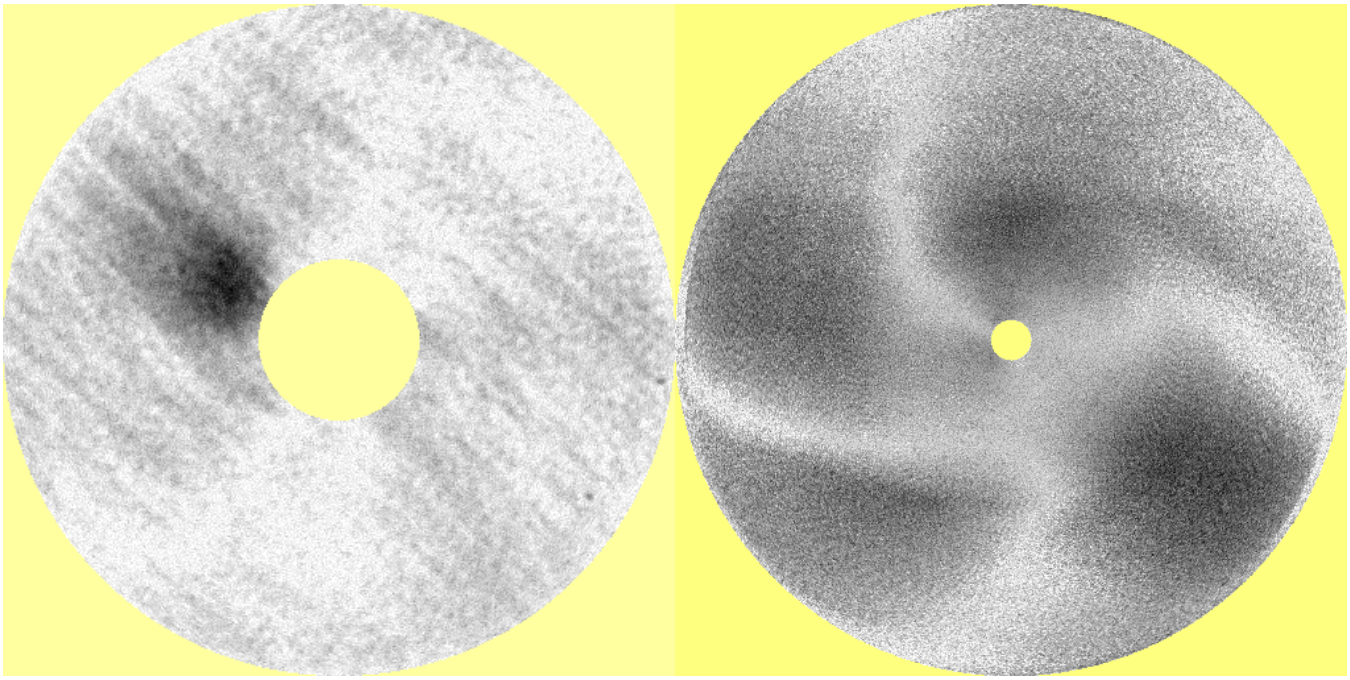
Disc 6 – side 2: DESY (left), SNS/FNAL (right);



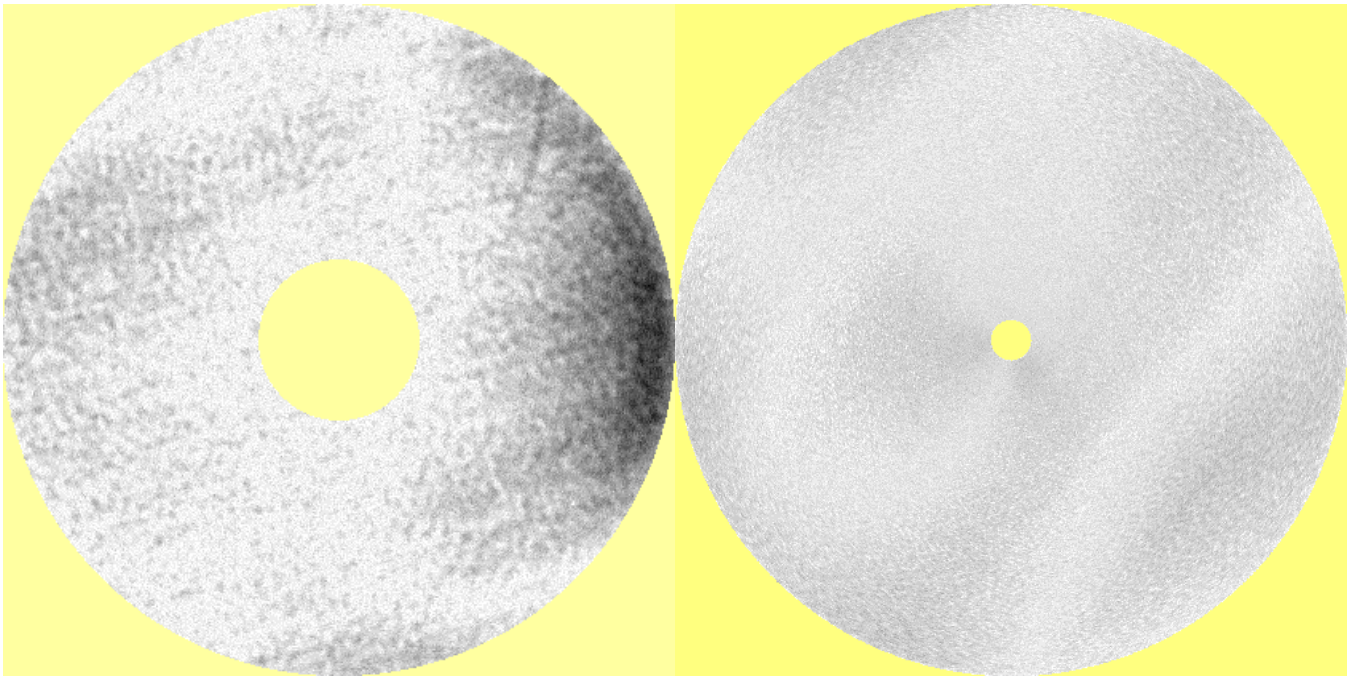
Disc 7 – side 1: DESY (left), SNS/FNAL (right);



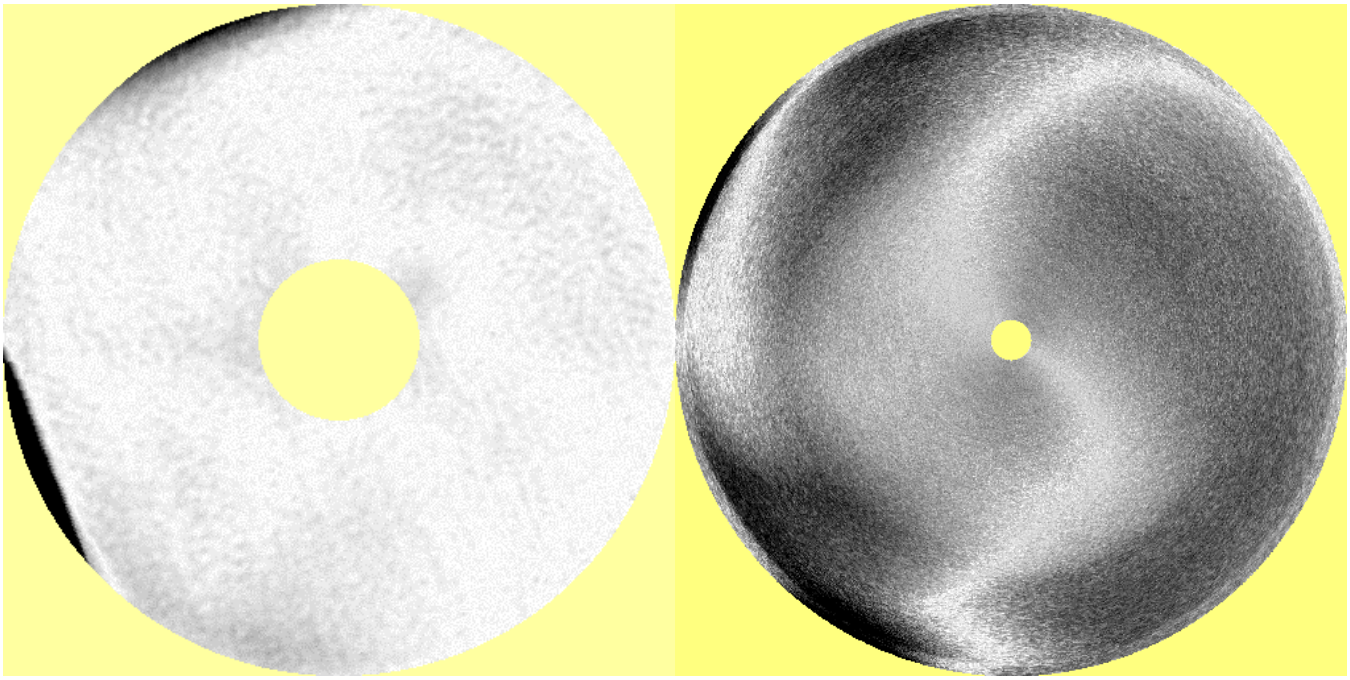
Disc 7 – side 2: DESY (left), disc did not fit SNS/FNAL scanner;



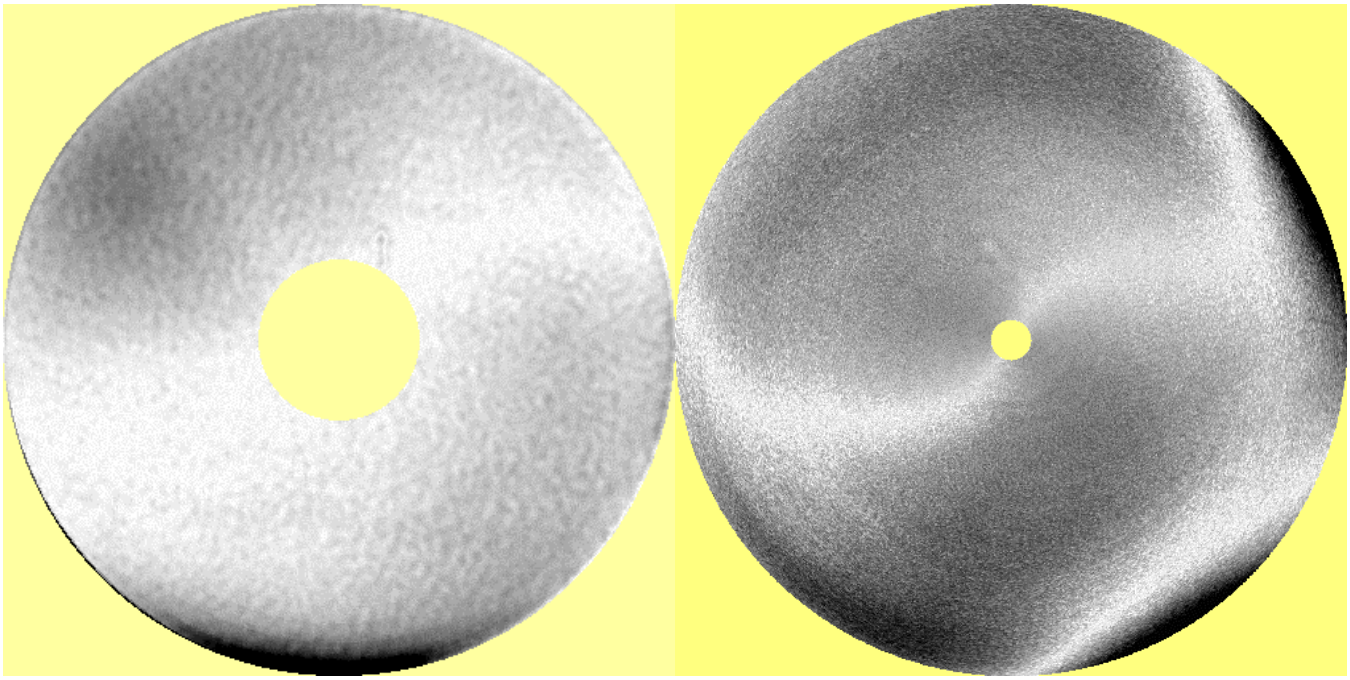
Disc 8 – side 1: DESY (left), SNS/FNAL (right), defect found in DESY scan;



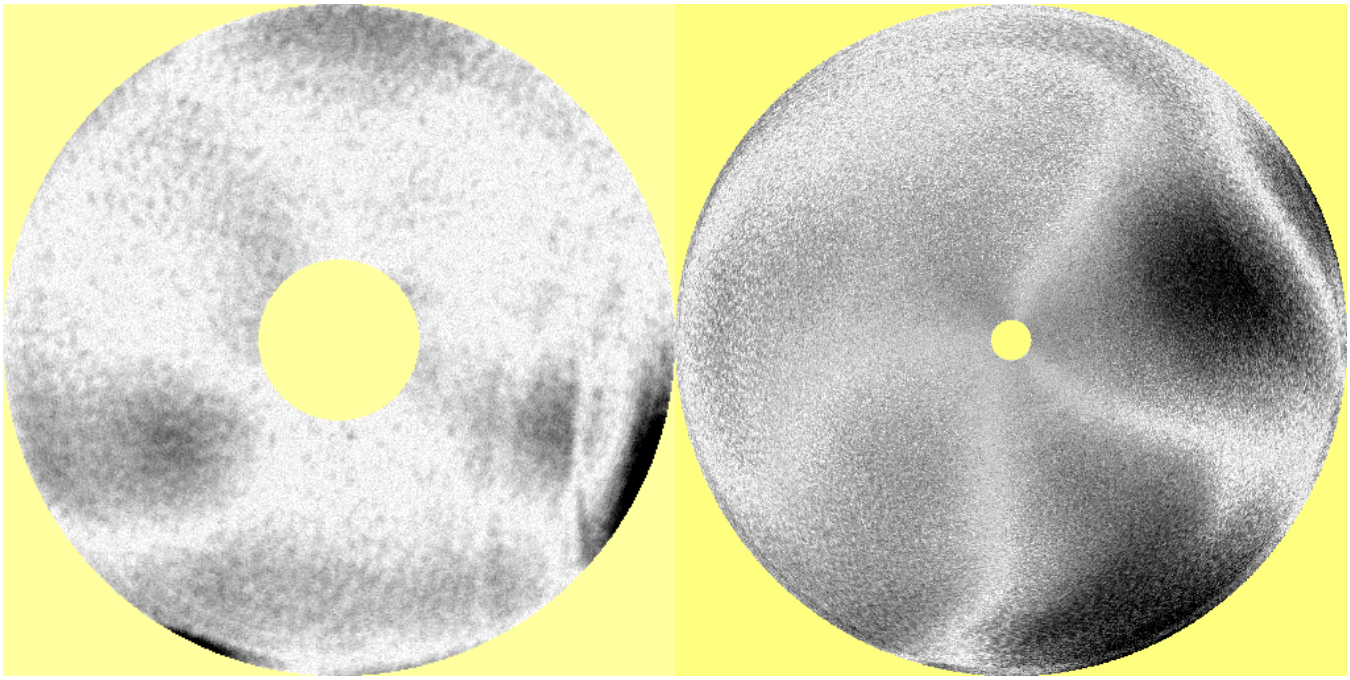
Disc 8 – side 2: DESY (left), SNS/FNAL (right);



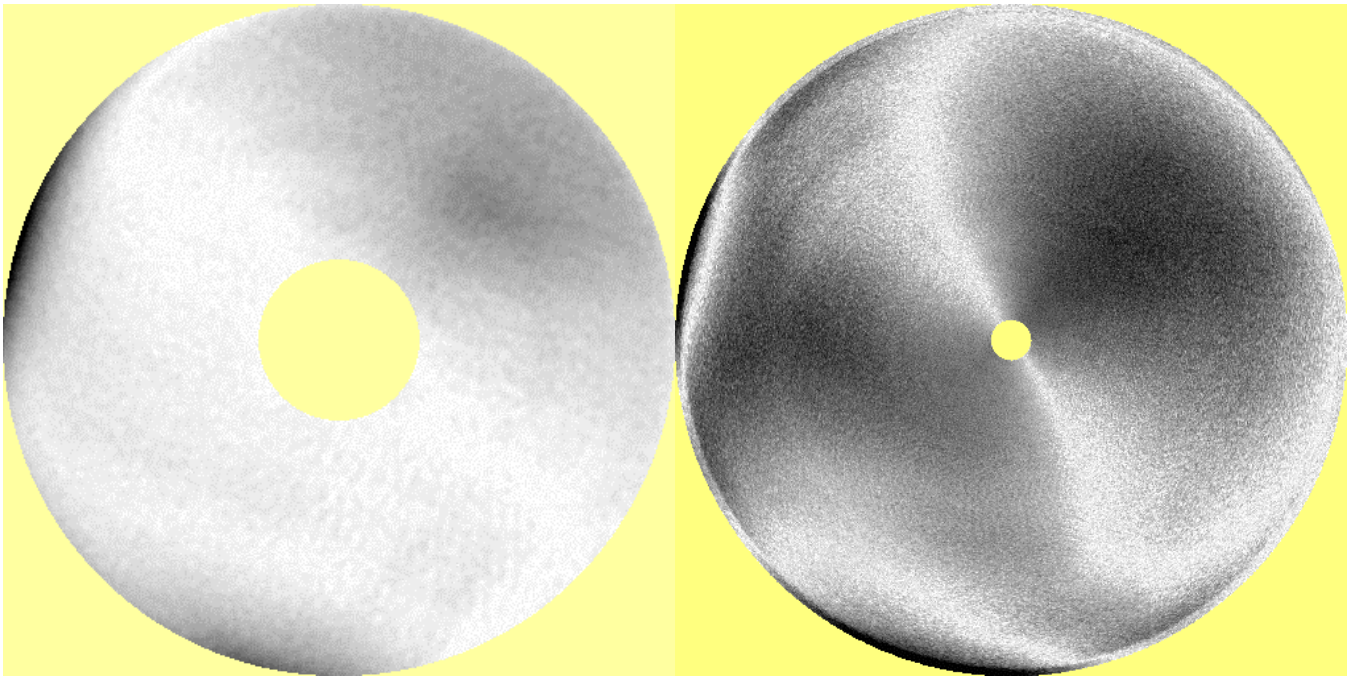
Disc 9 – side 1: DESY (left), SNS/FNAL (right);



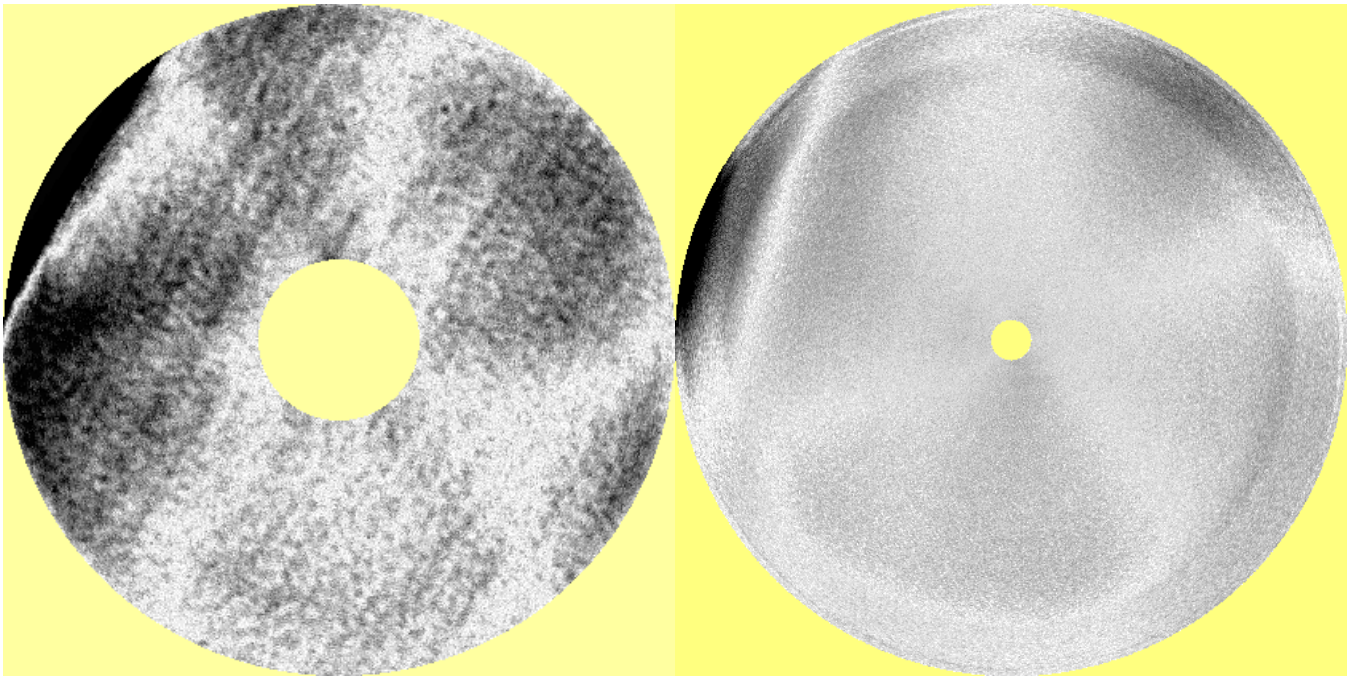
Disc 9 – side 2: DESY (left), SNS/FNAL (right);



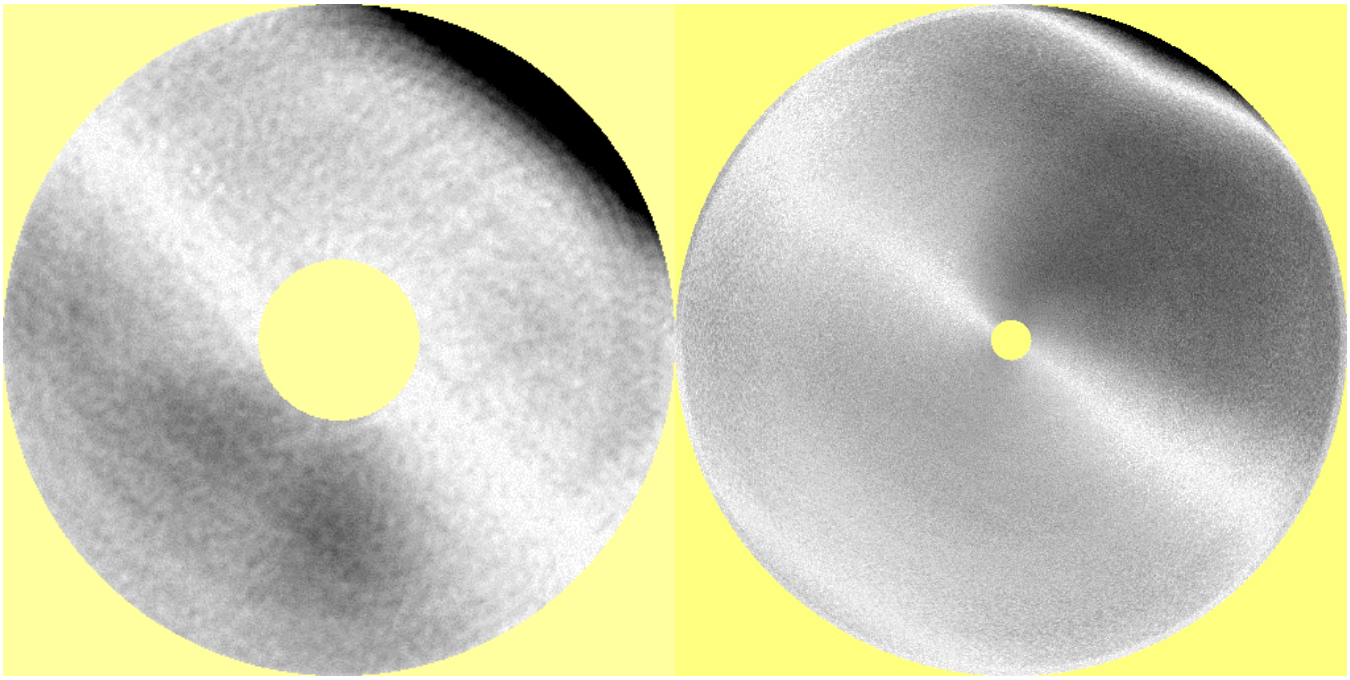
Disc 10 – side 1: DESY (left), SNS/FNAL (right);



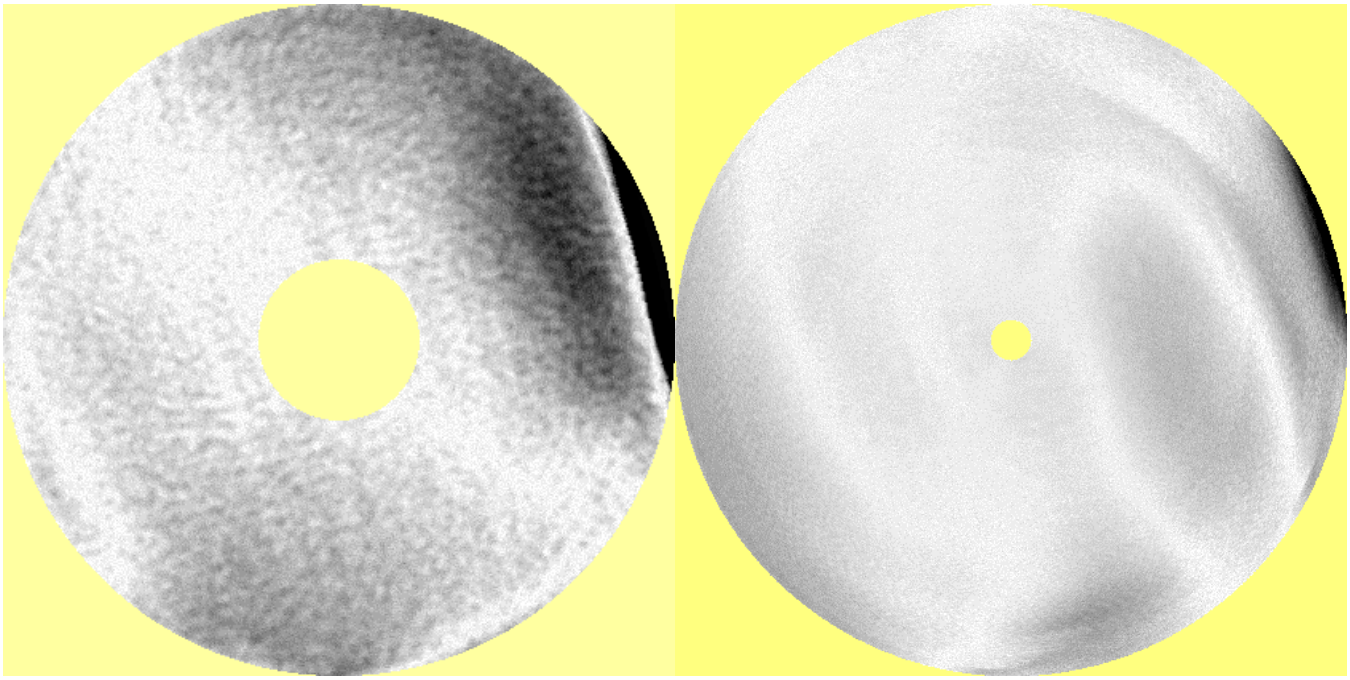
Disc 10 – side 2: DESY (left), SNS/FNAL (right);



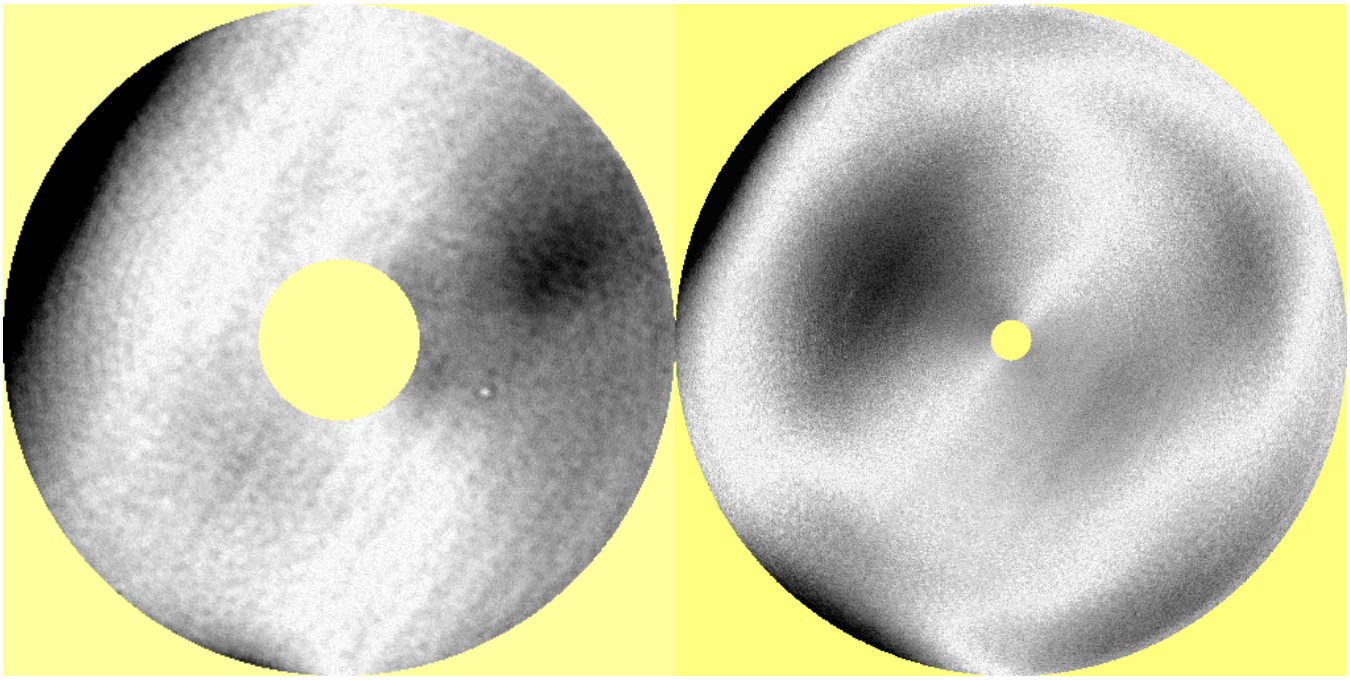
Disc 11 – side 1: DESY (left), SNS/FNAL (right);



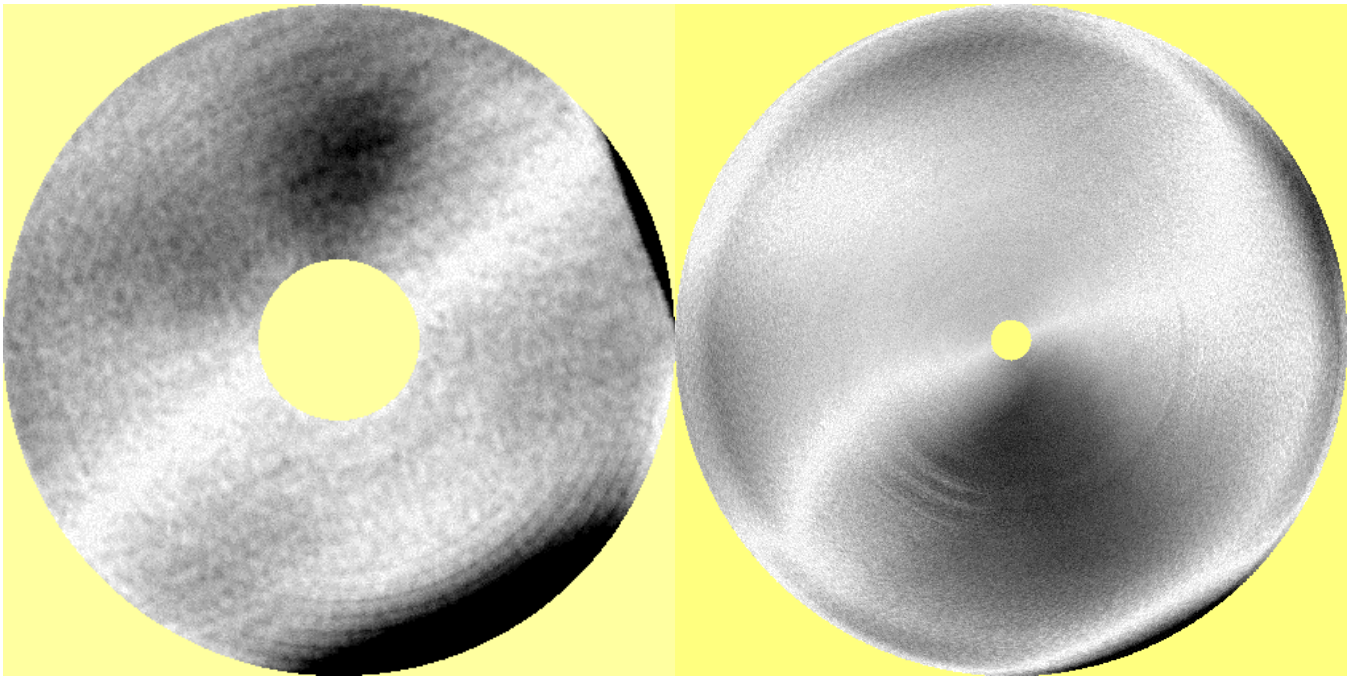
Disc 11 – side 2: DESY (left), SNS/FNAL (right);



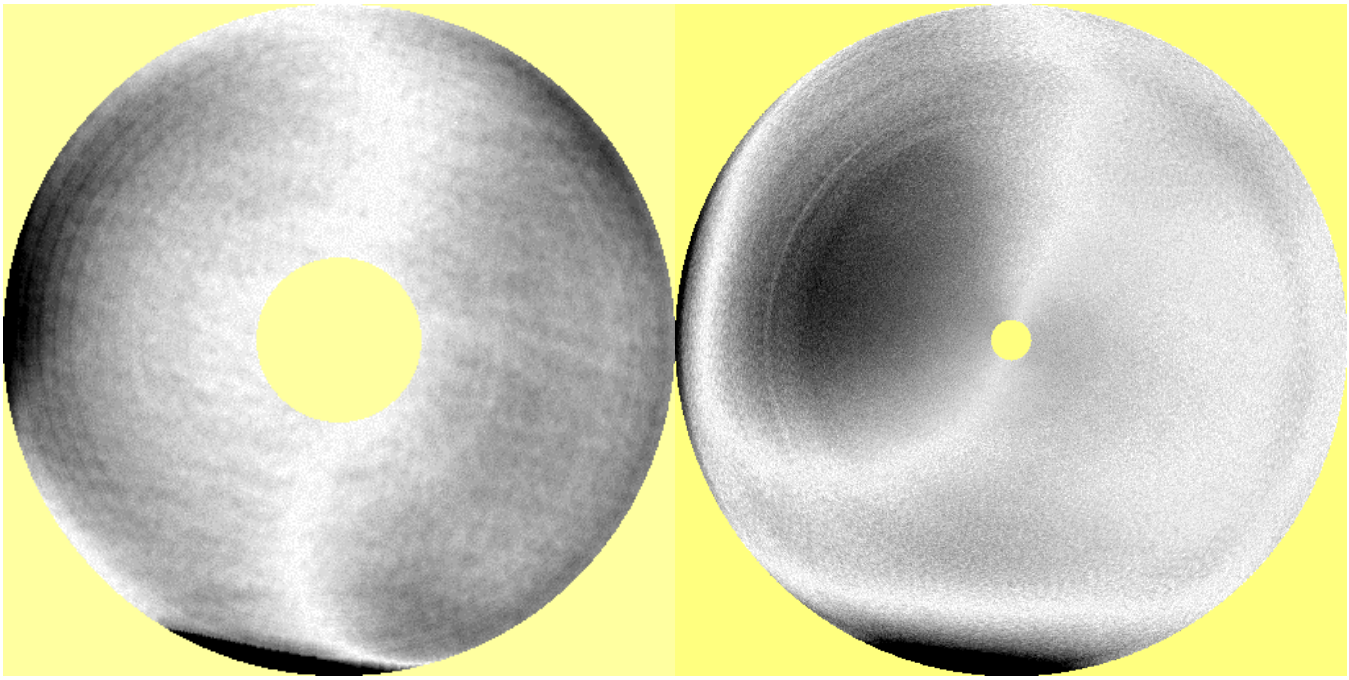
Disc 12 – side 1: DESY (left), SNS/FNAL (right);



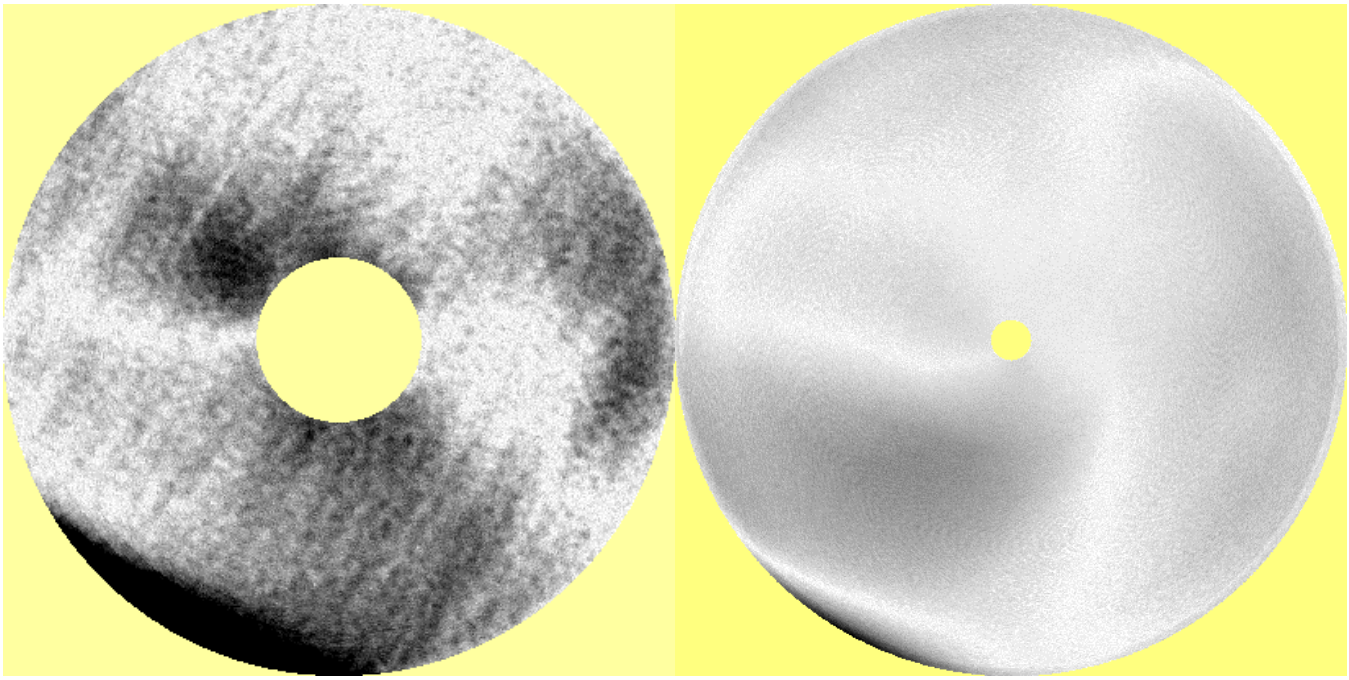
Disc 12 – side 2: DESY (left), SNS/FNAL (right), defect found in DESY scan;



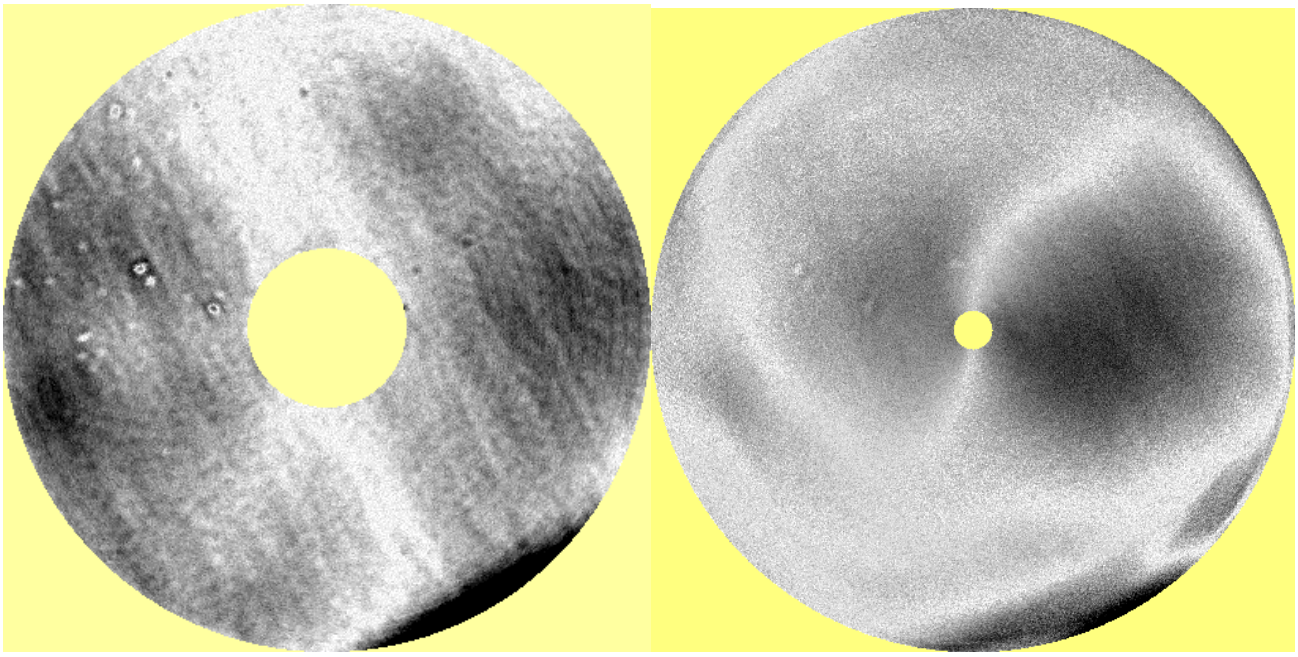
Disc 13 – side 1: DESY (left), SNS/FNAL (right);



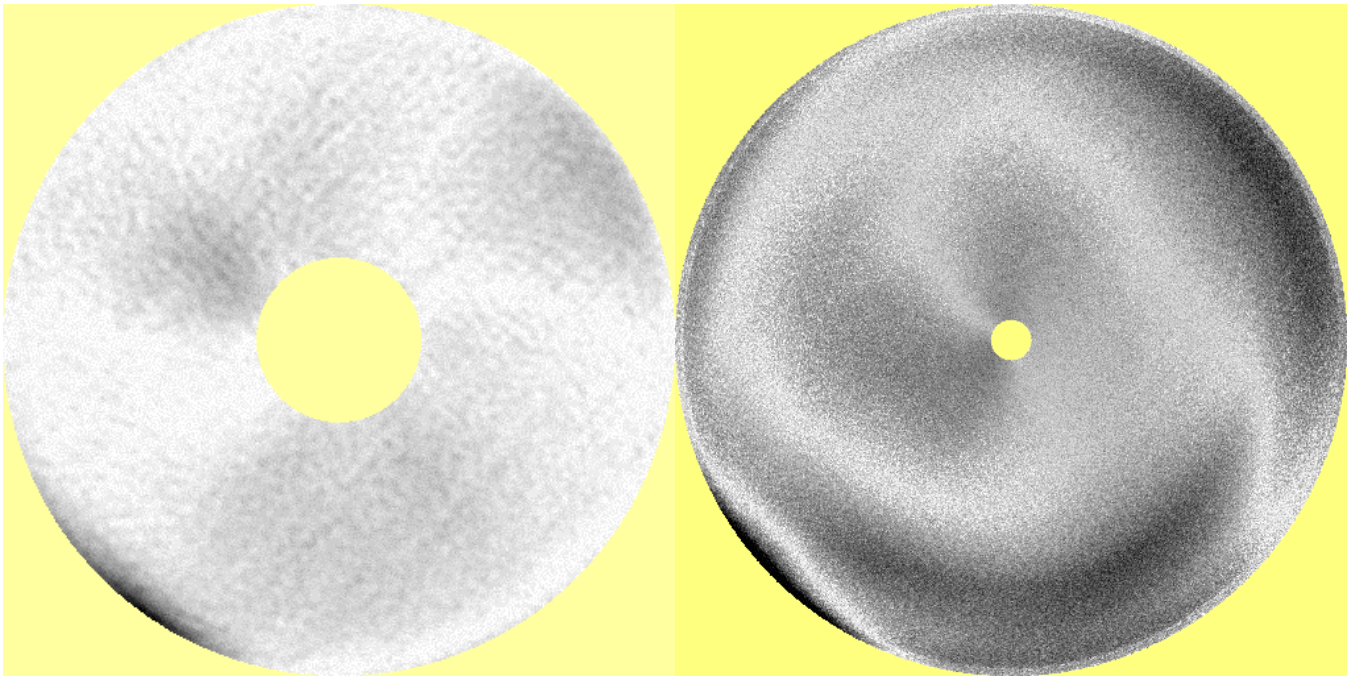
Disc 13 – side 2: DESY (left), SNS/FNAL (right);



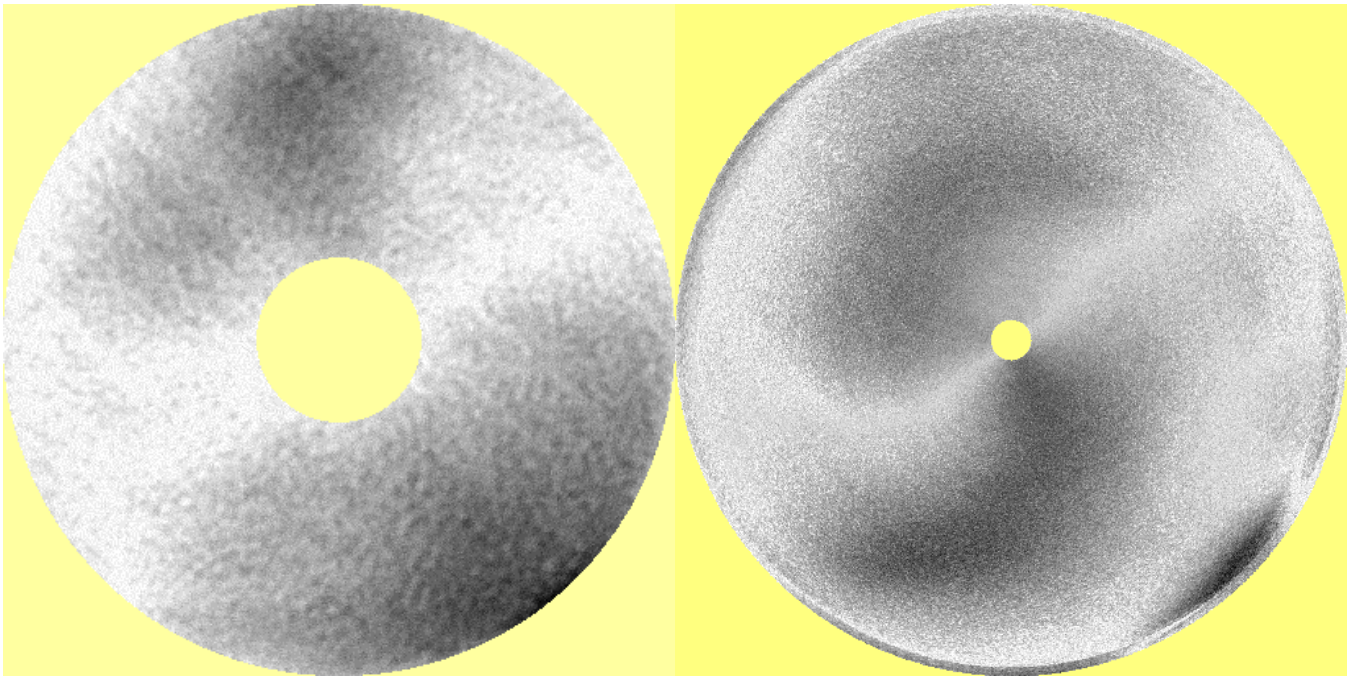
Disc 14 – side 1: DESY (left), SNS/FNAL (right);



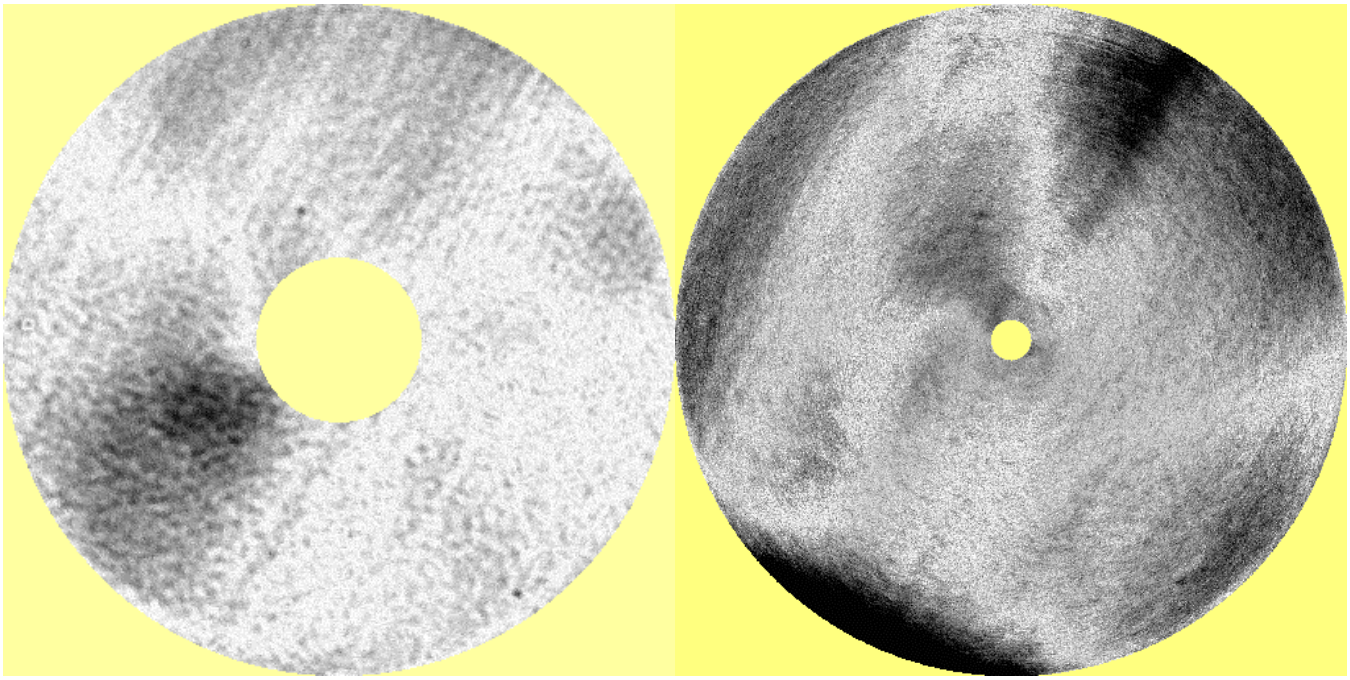
Disc 14 – side 2: DESY (left), SNS/FNAL (right), defects found in DESY scan;



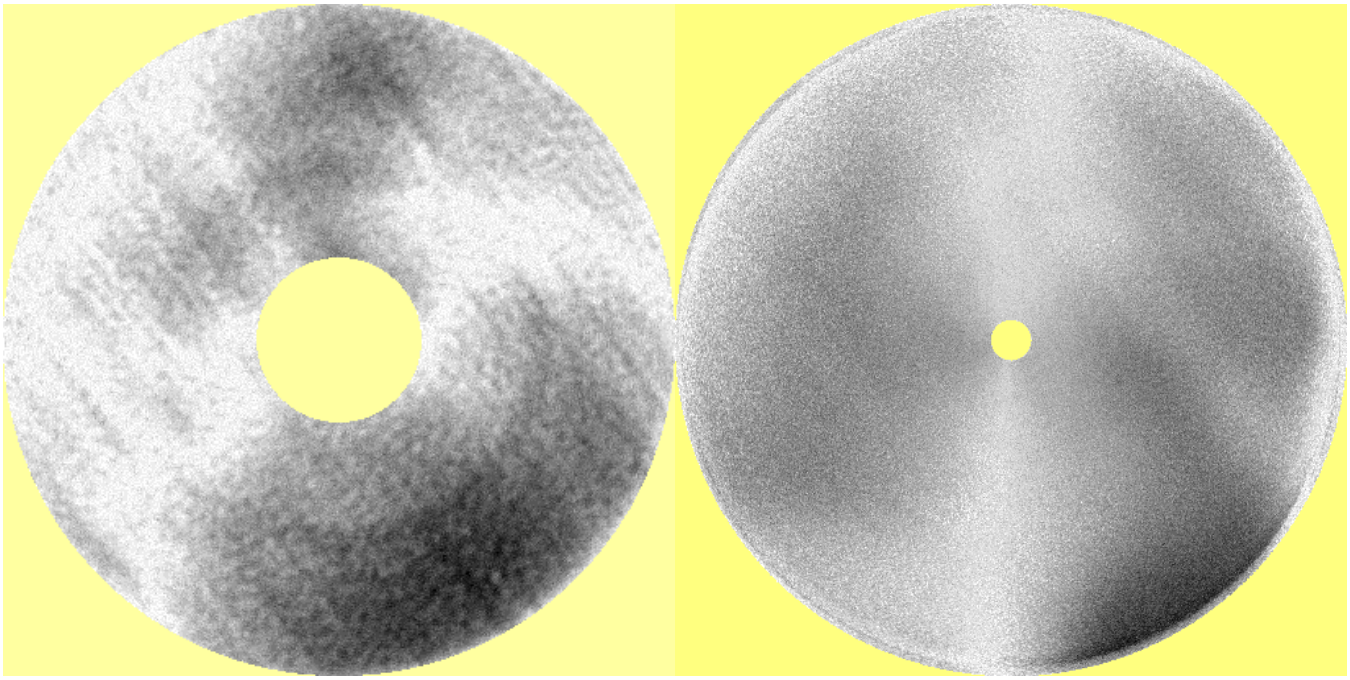
Disc 15 – side 1: DESY (left), SNS/FNAL (right);



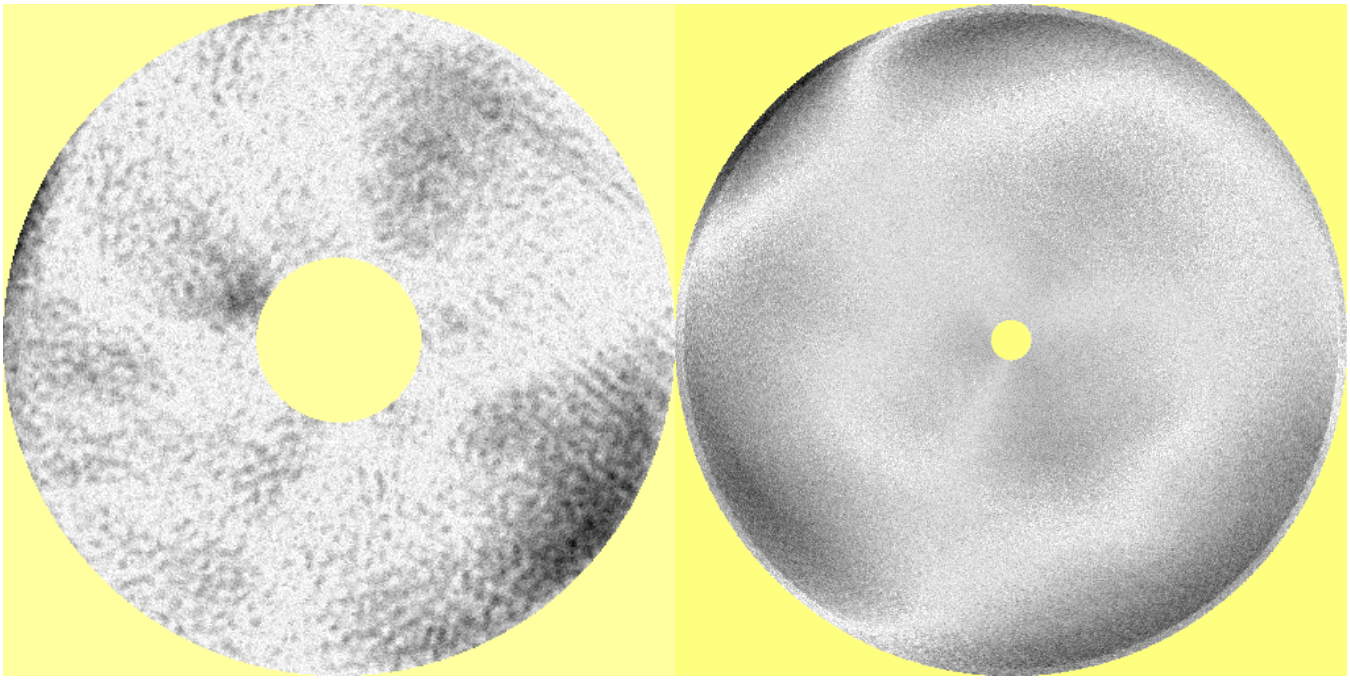
Disc 15 – side 2: DESY (left), SNS/FNAL (right);



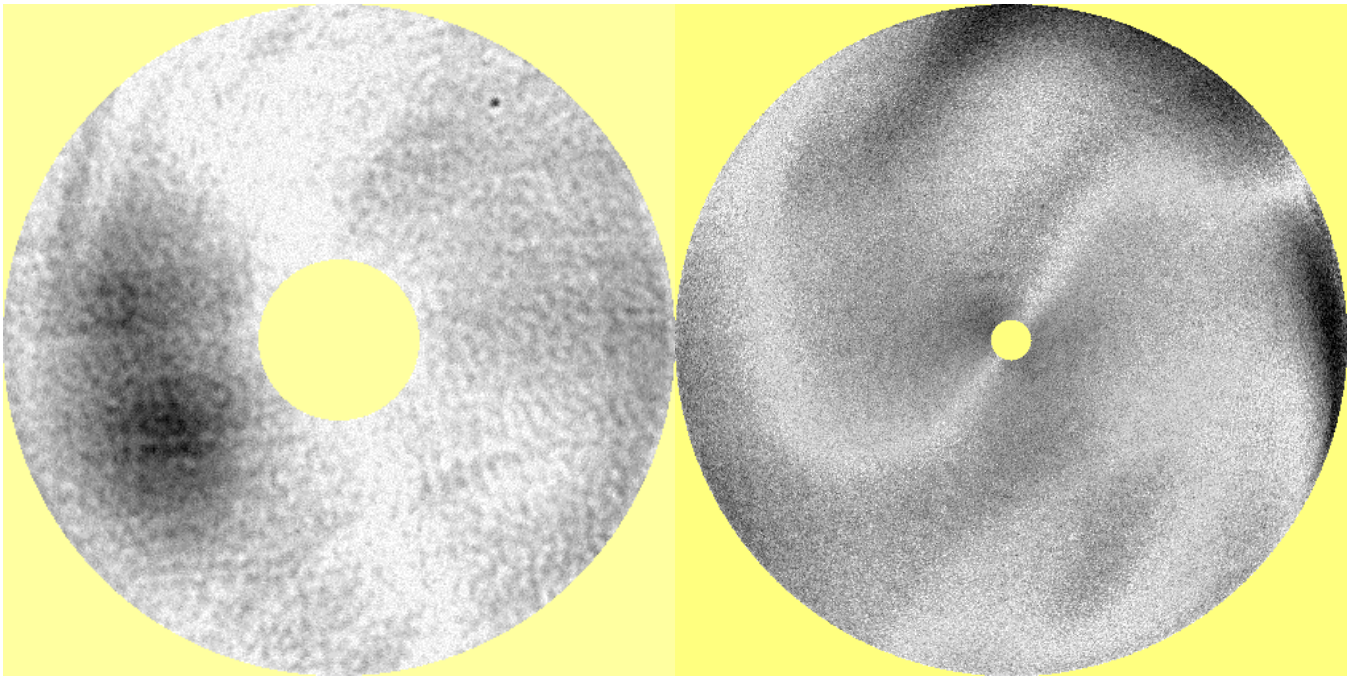
Disc 17 – side 1: DESY (left), SNS/FNAL (right), defect found in DESY scan;



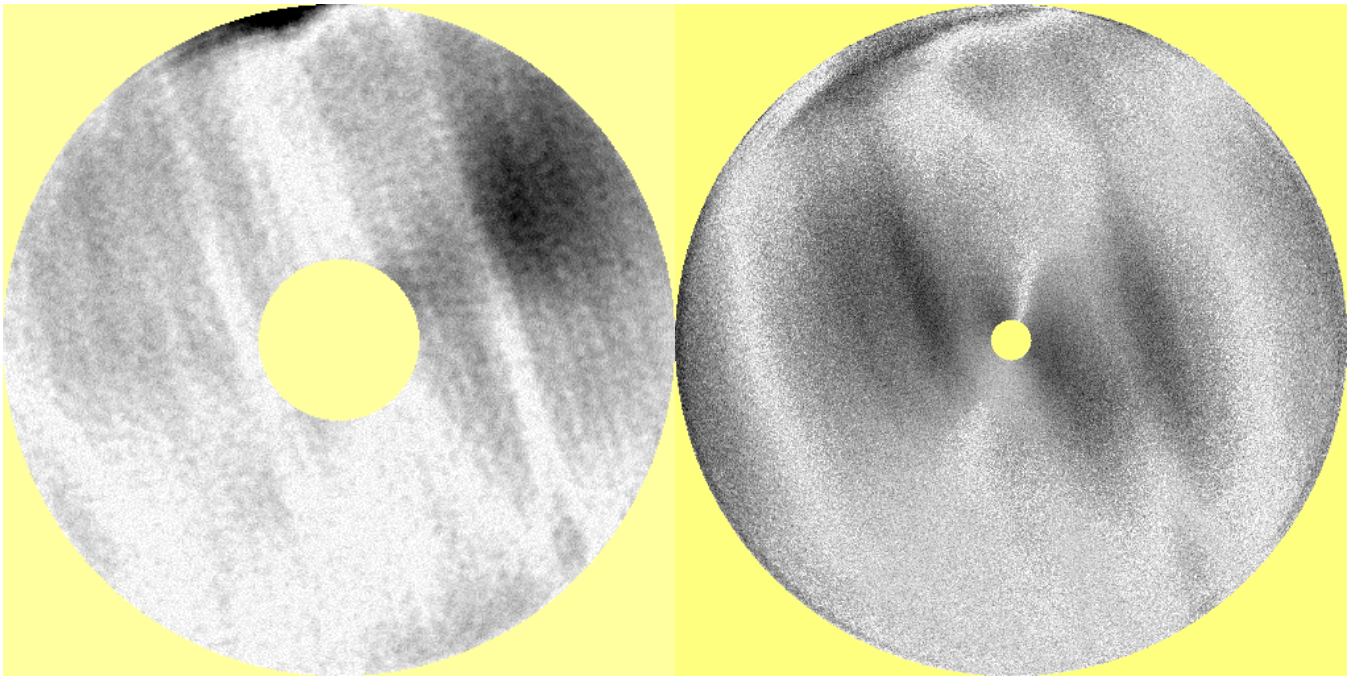
Disc 17 – side 2: DESY (left), SNS/FNAL (right);



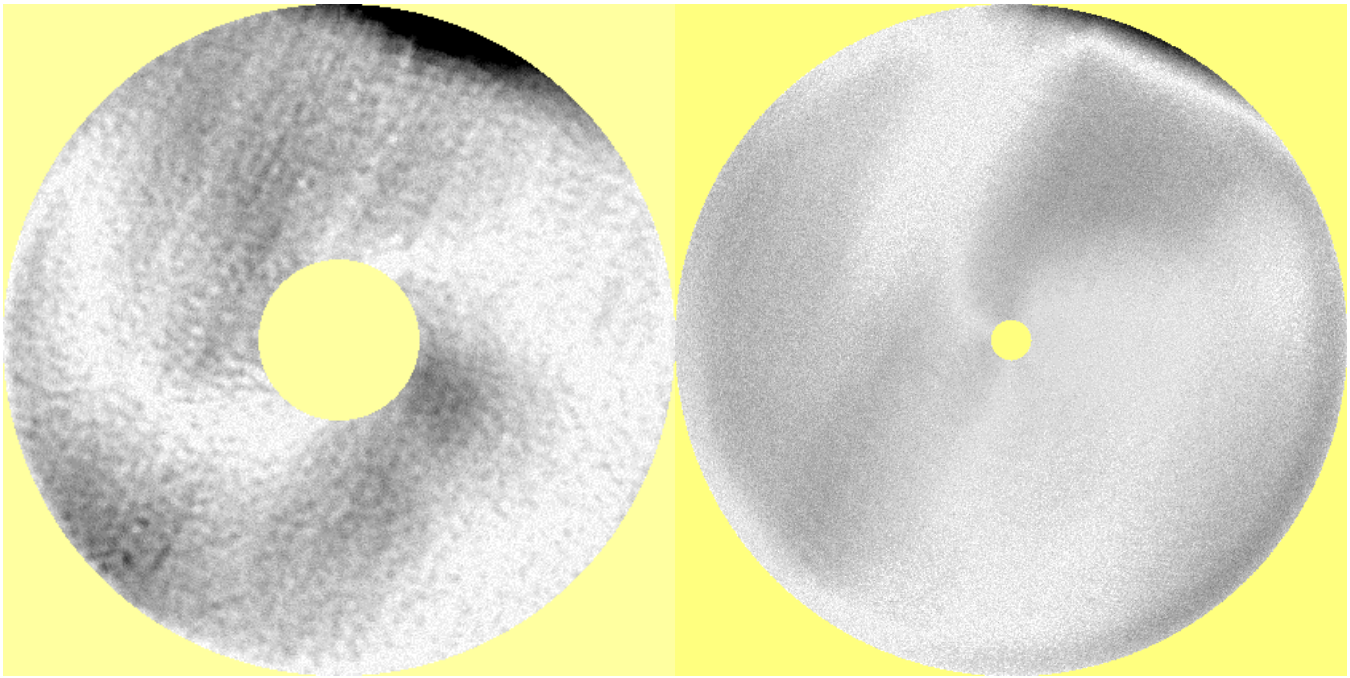
Disc 19 – side 1: DESY (left), SNS/FNAL (right);



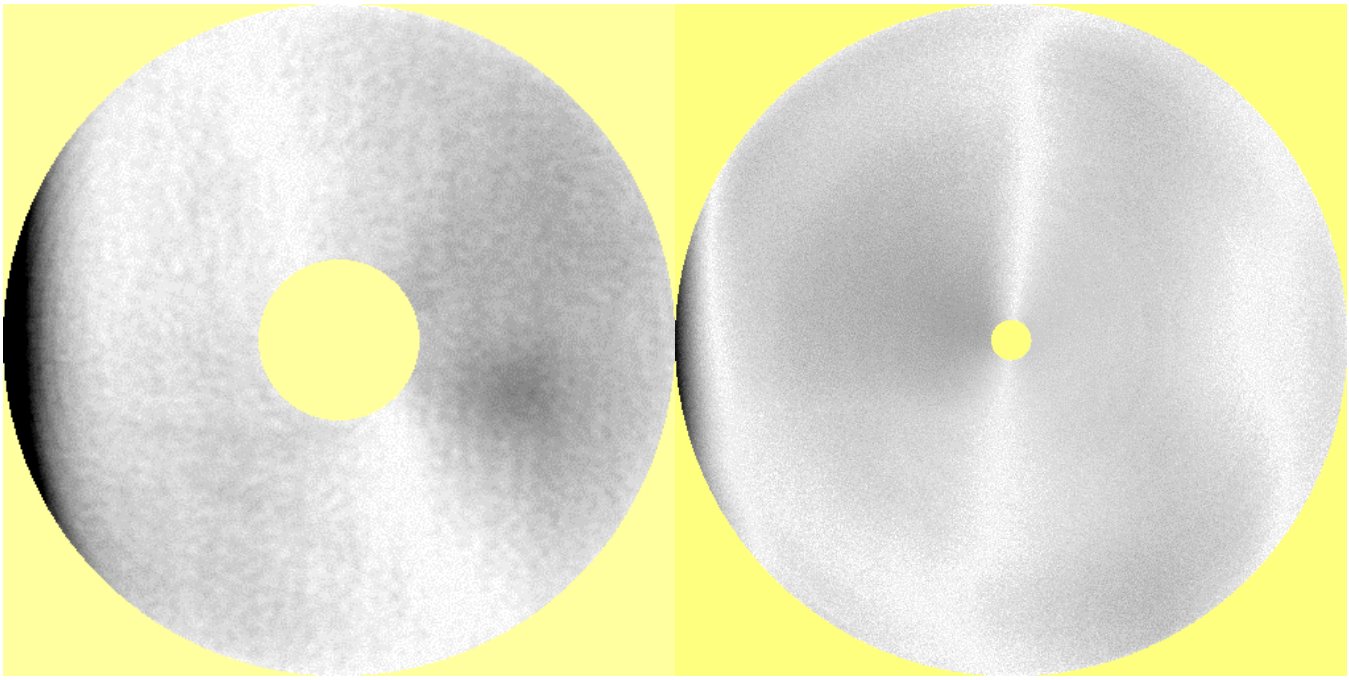
Disc 19 – side 2: DESY (left), SNS/FNAL (right), defect found in DESY scan;



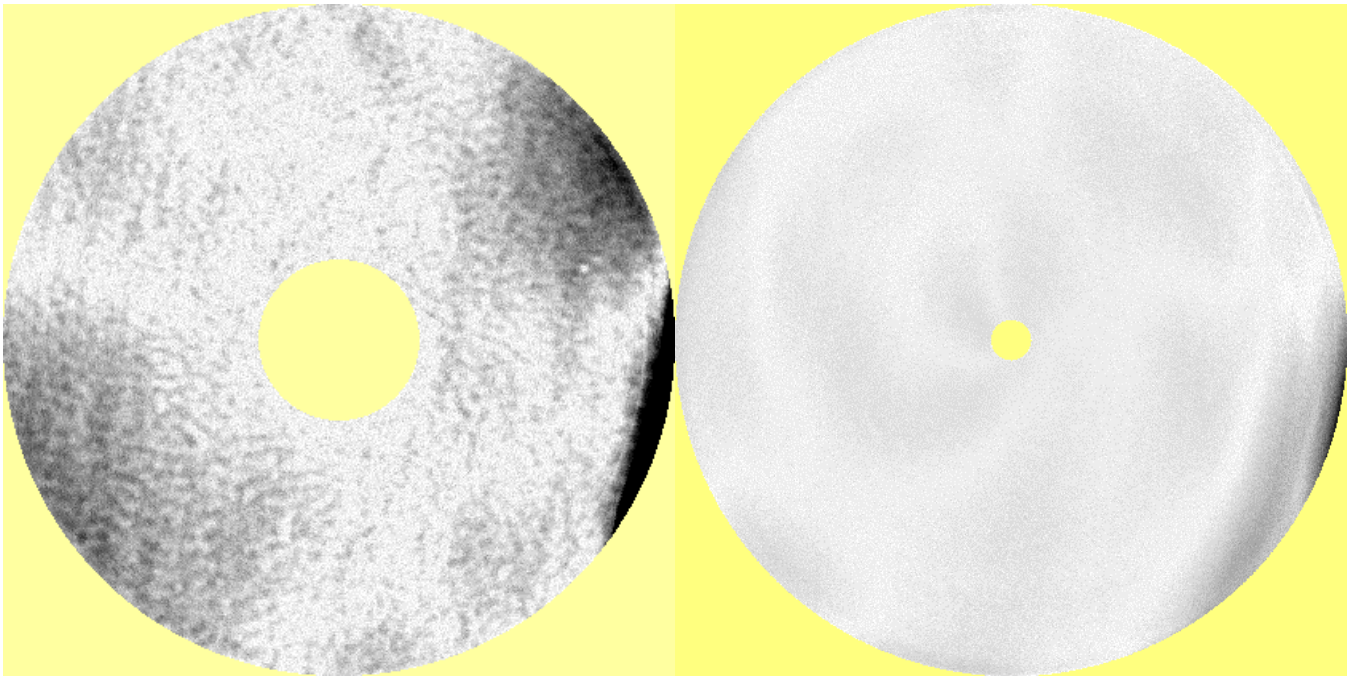
Disc 20 – side 1: DESY (left), SNS/FNAL (right);



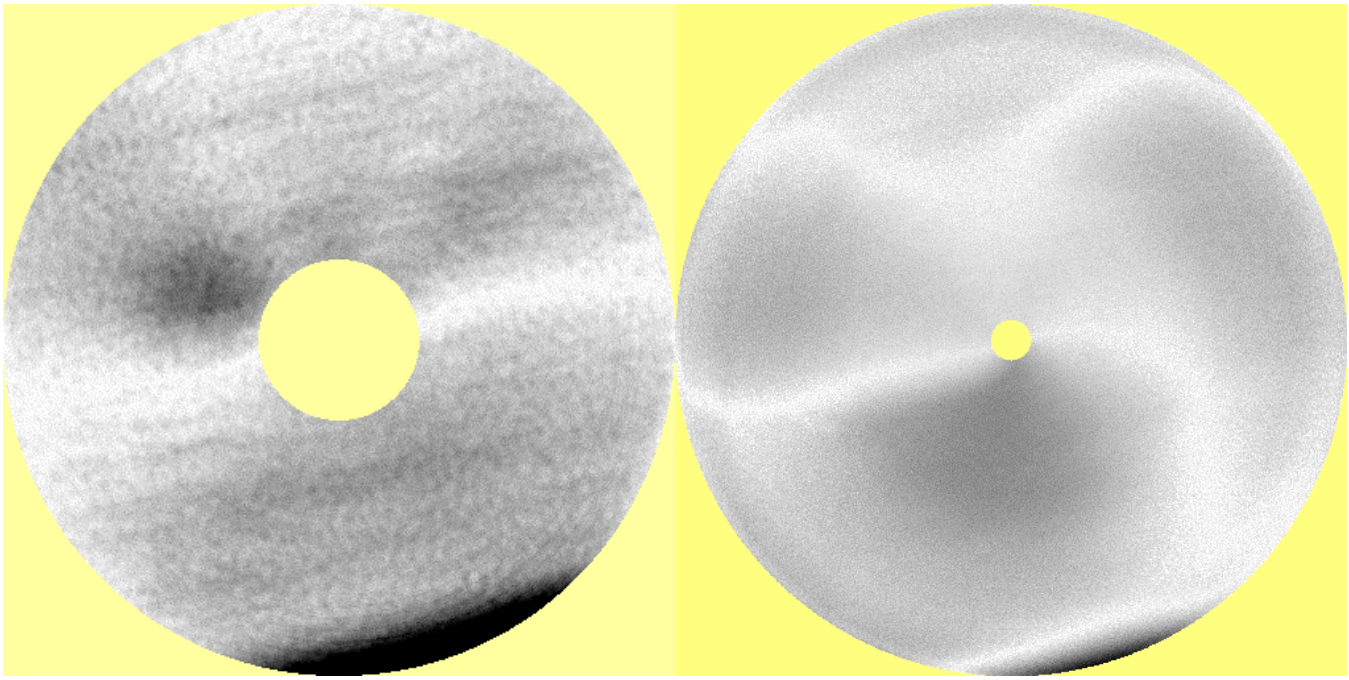
Disc 20 – side 2: DESY (left), SNS/FNAL (right);



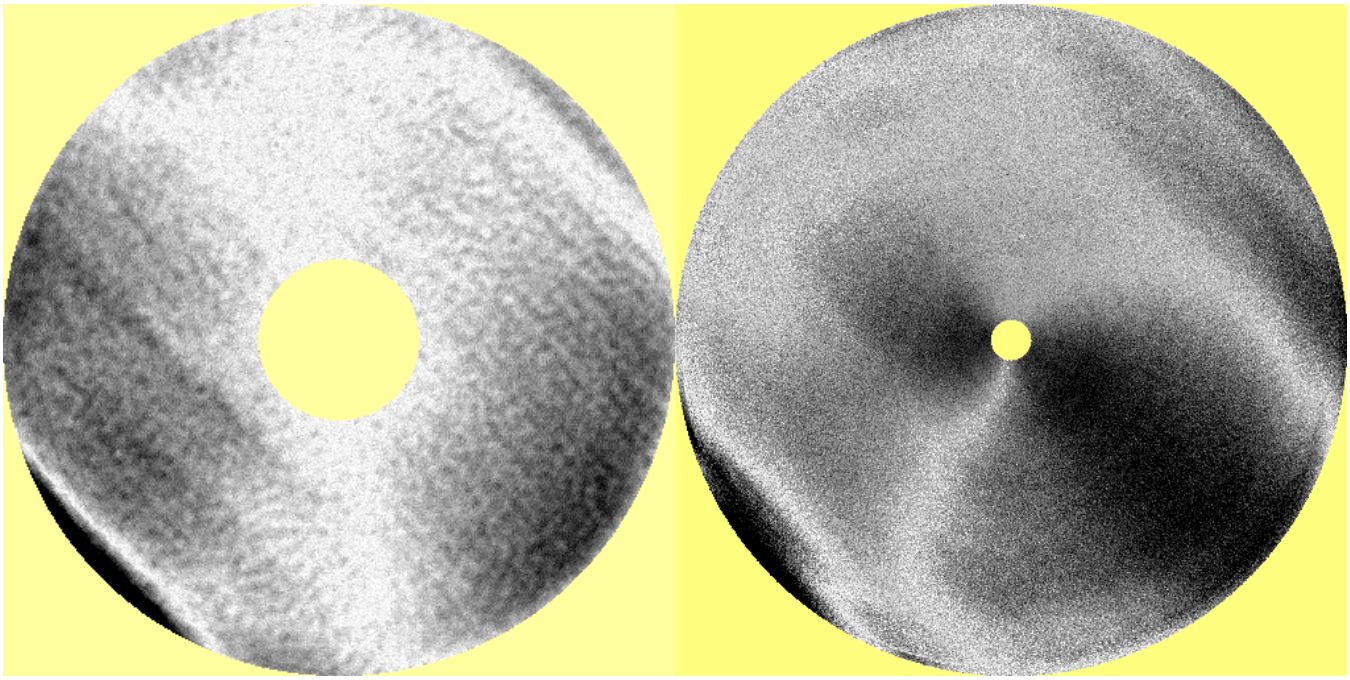
Disc 21 – side 1: DESY (left), SNS/FNAL (right);



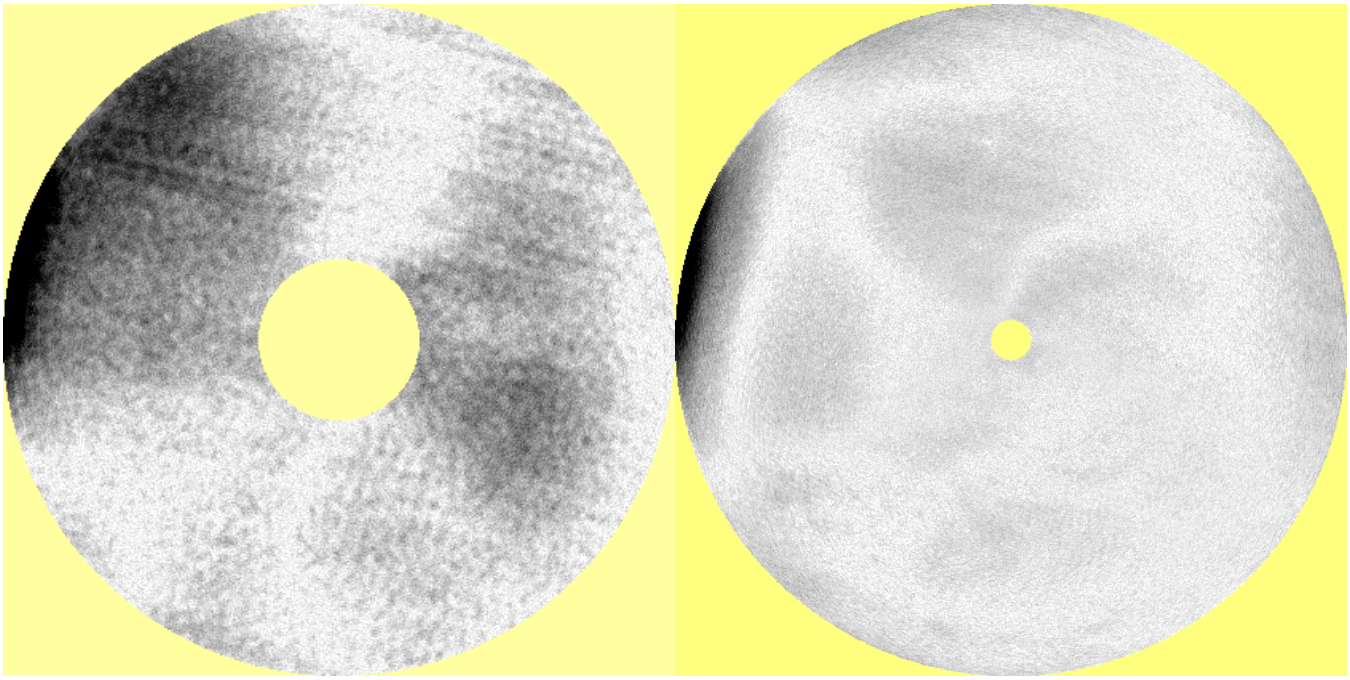
Disc 21 – side 2: DESY (left), SNS/FNAL (right);



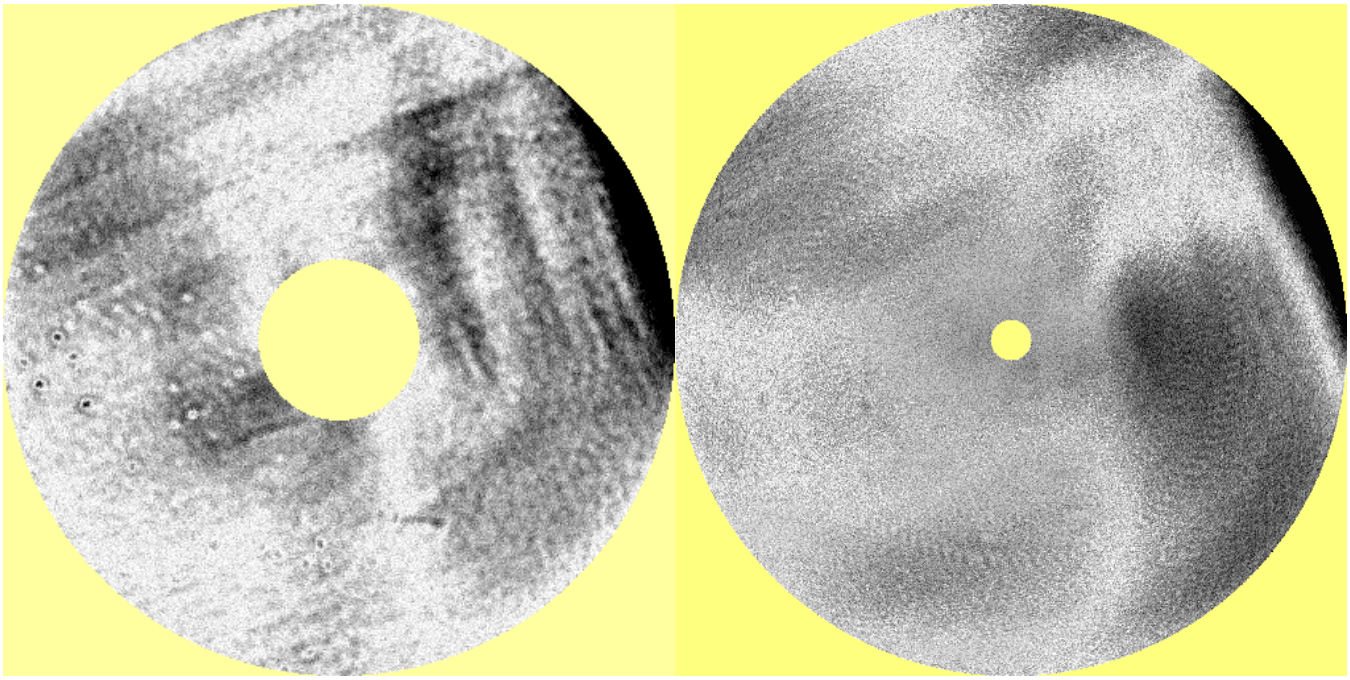
Disc 24 – side 1: DESY (left), SNS/FNAL (right);



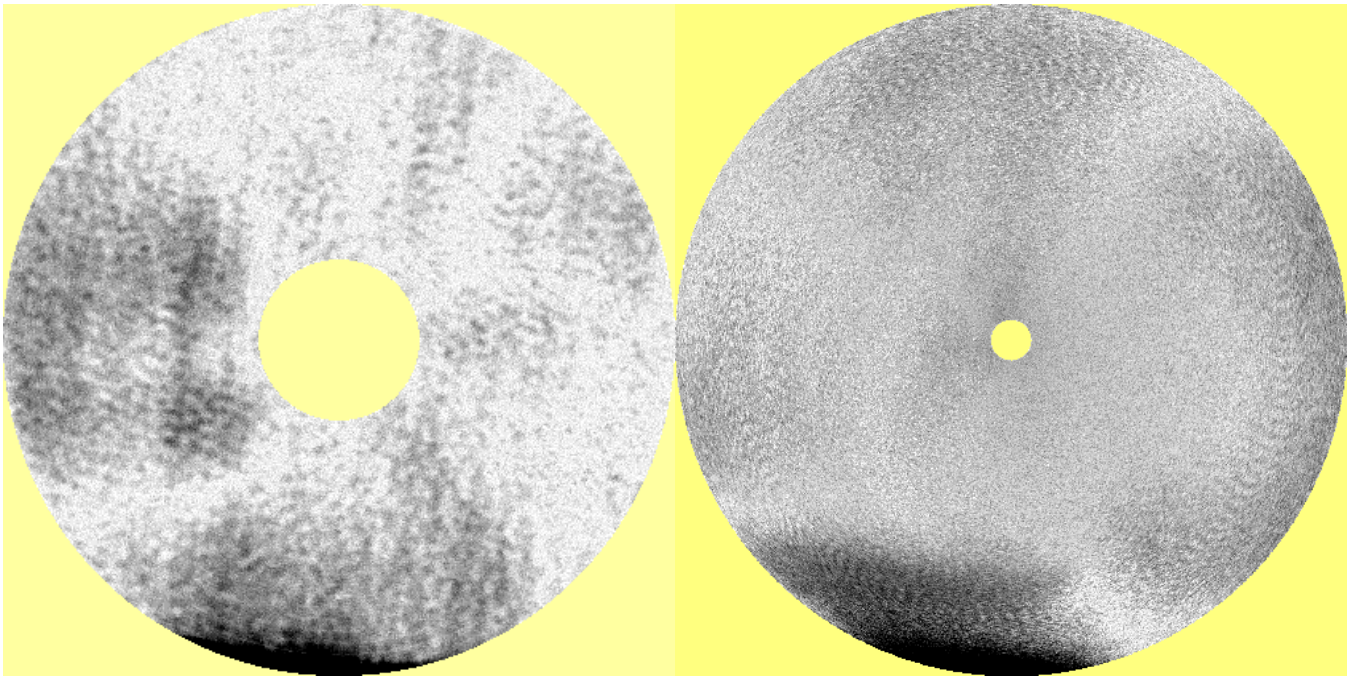
Disc 24 – side 2: DESY (left), SNS/FNAL (right);



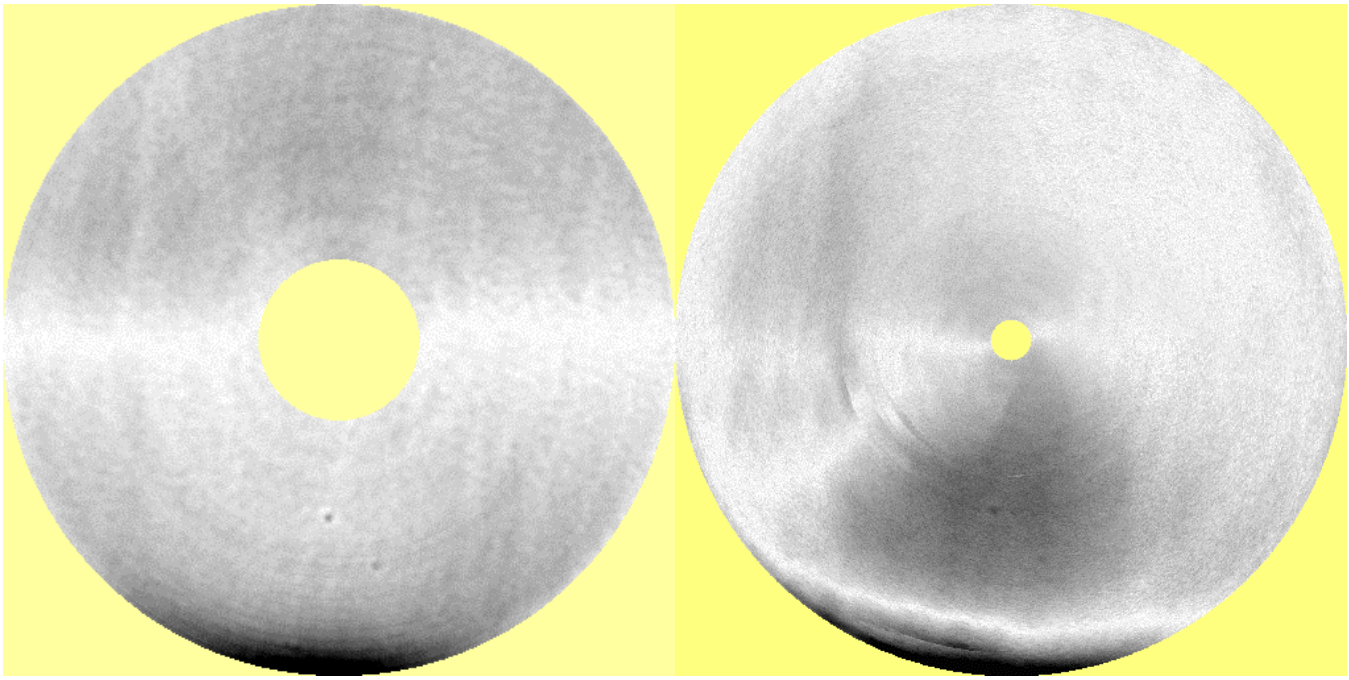
Disc 27– side 1: DESY (left), SNS/FNAL (right);



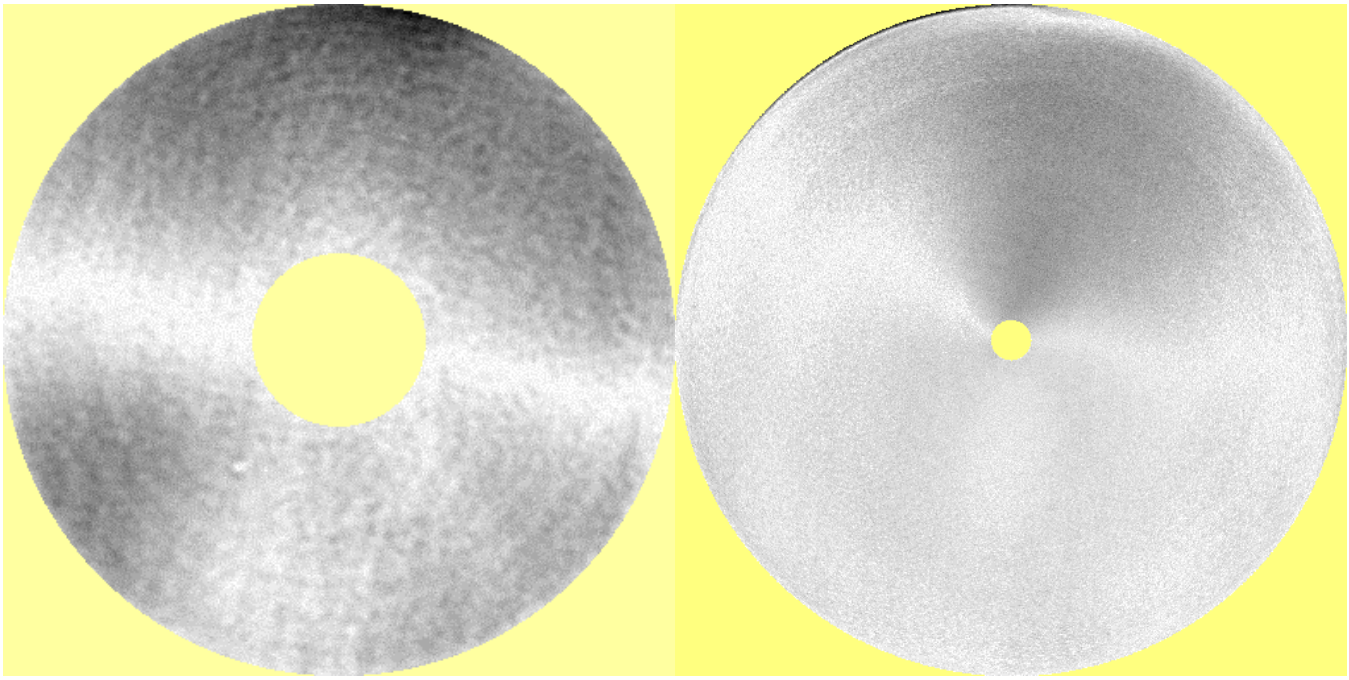
Disc 27 – side 2: DESY (left), SNS/FNAL (right), defects found in DESY scan;



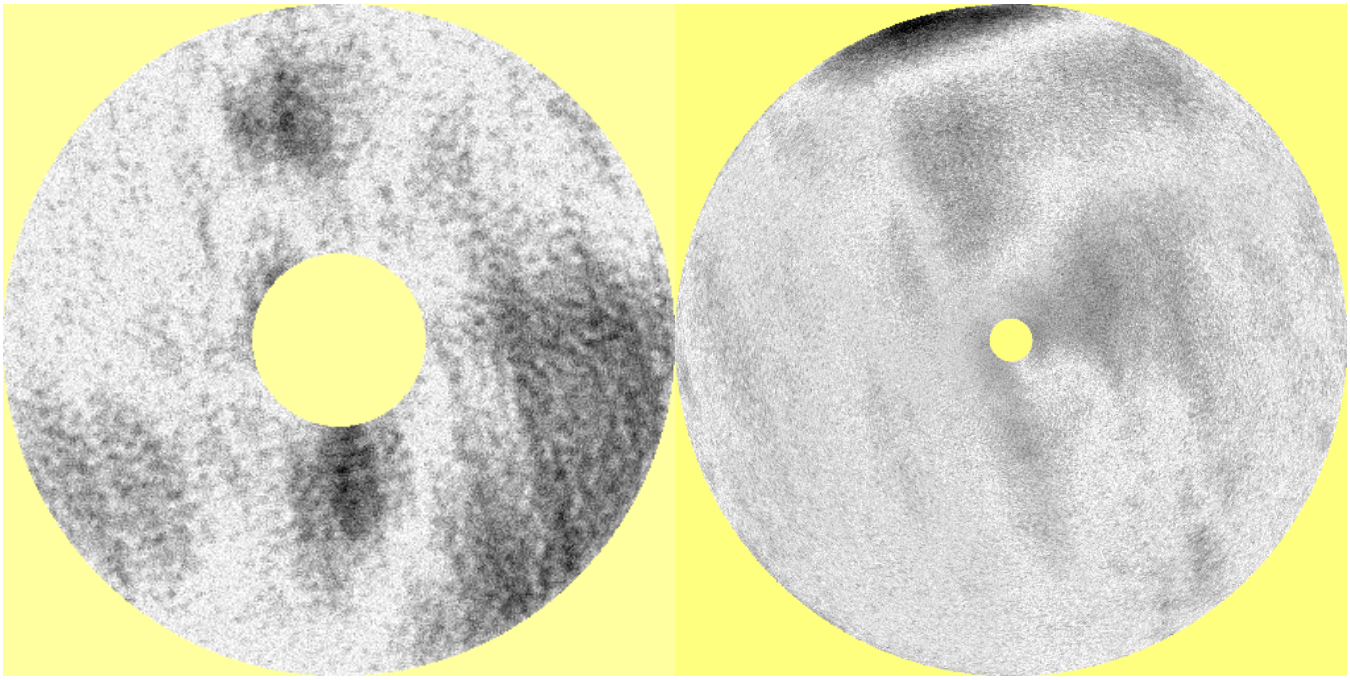
Disc 32 – side 1: DESY (left), SNS/FNAL (right);



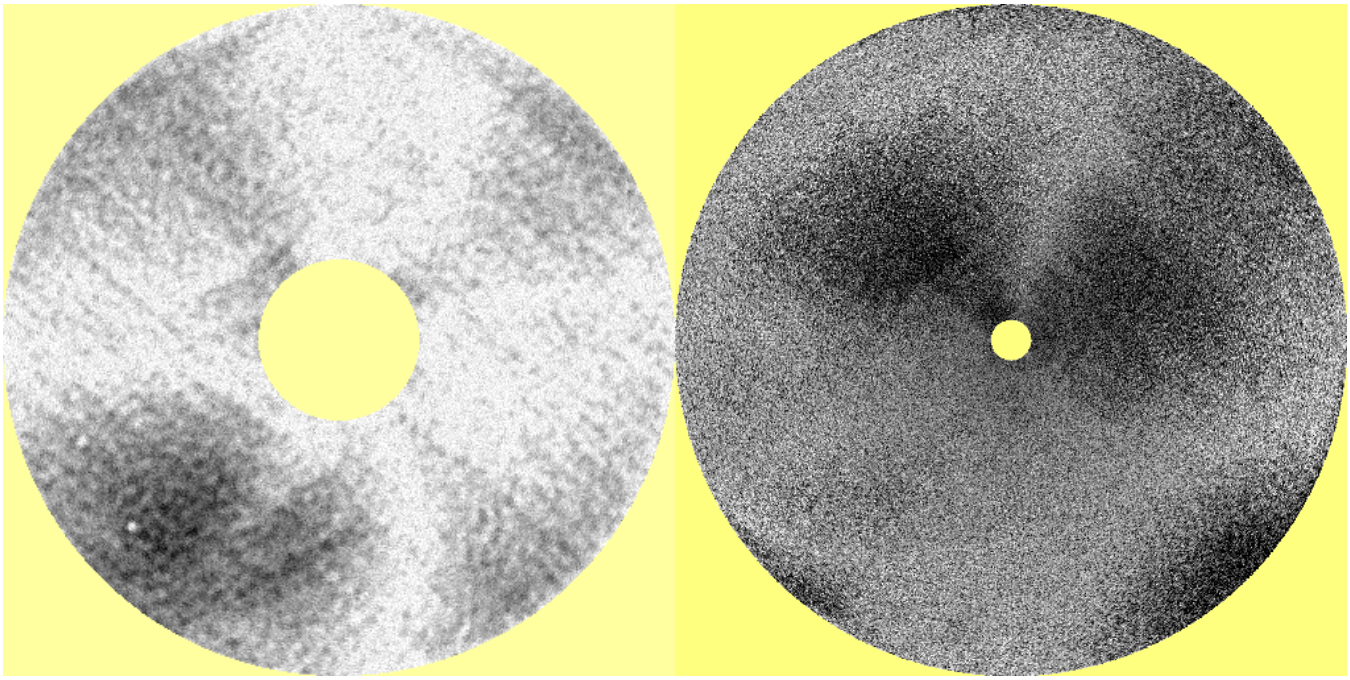
Disc 32 – side 2: DESY (left), SNS/FNAL (right), defects found in DESY scan;



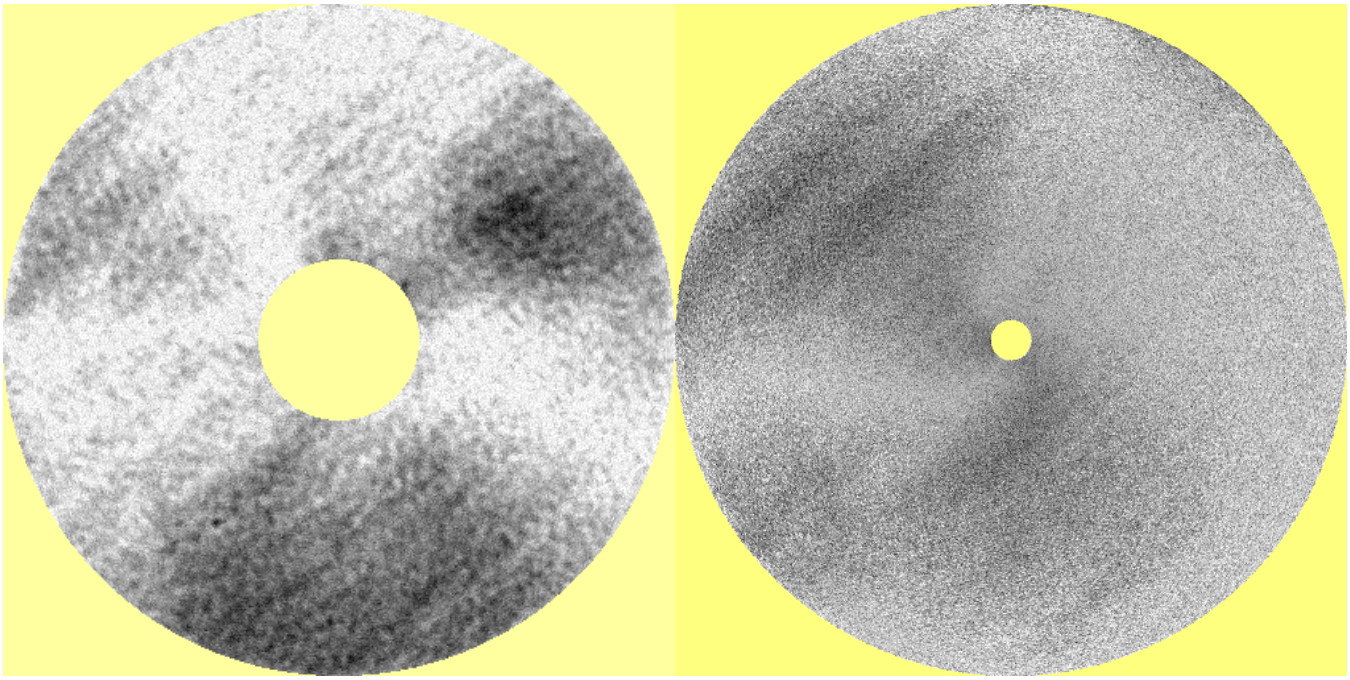
Disc 33 – side 1: DESY (left), SNS/FNAL (right);



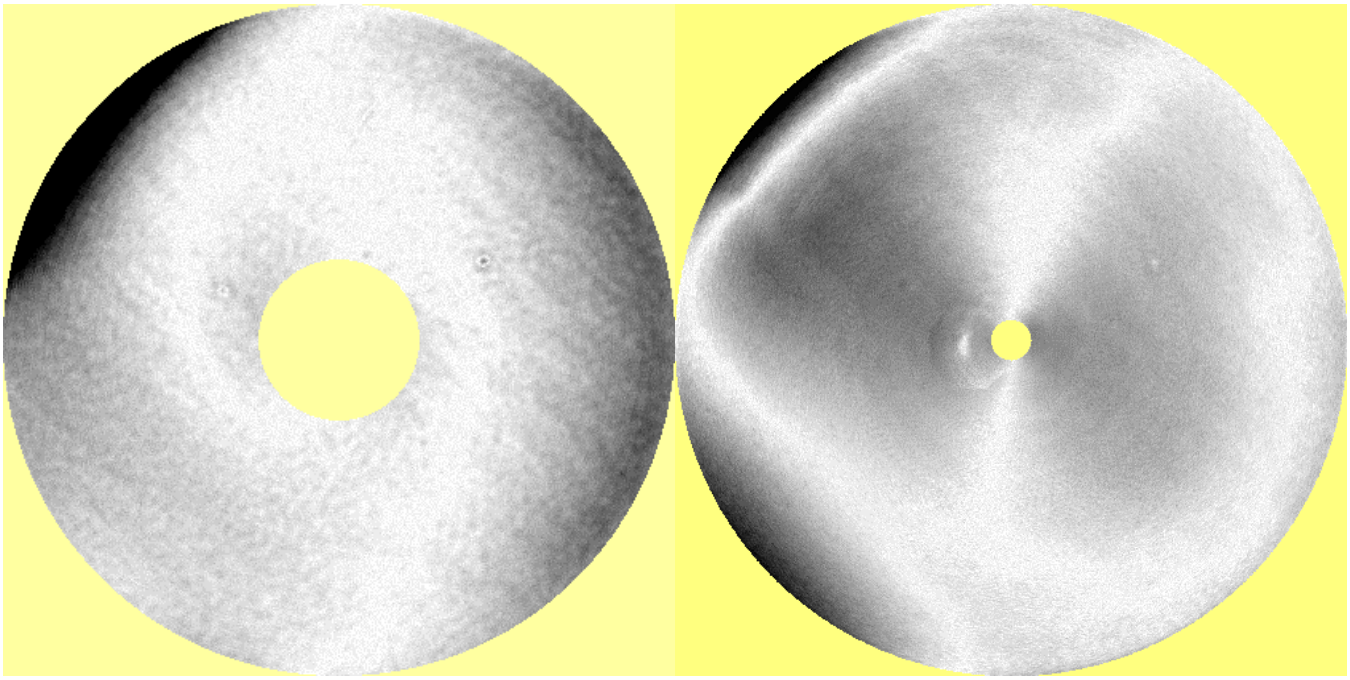
Disc 33 – side 2: DESY (left), SNS/FNAL (right);



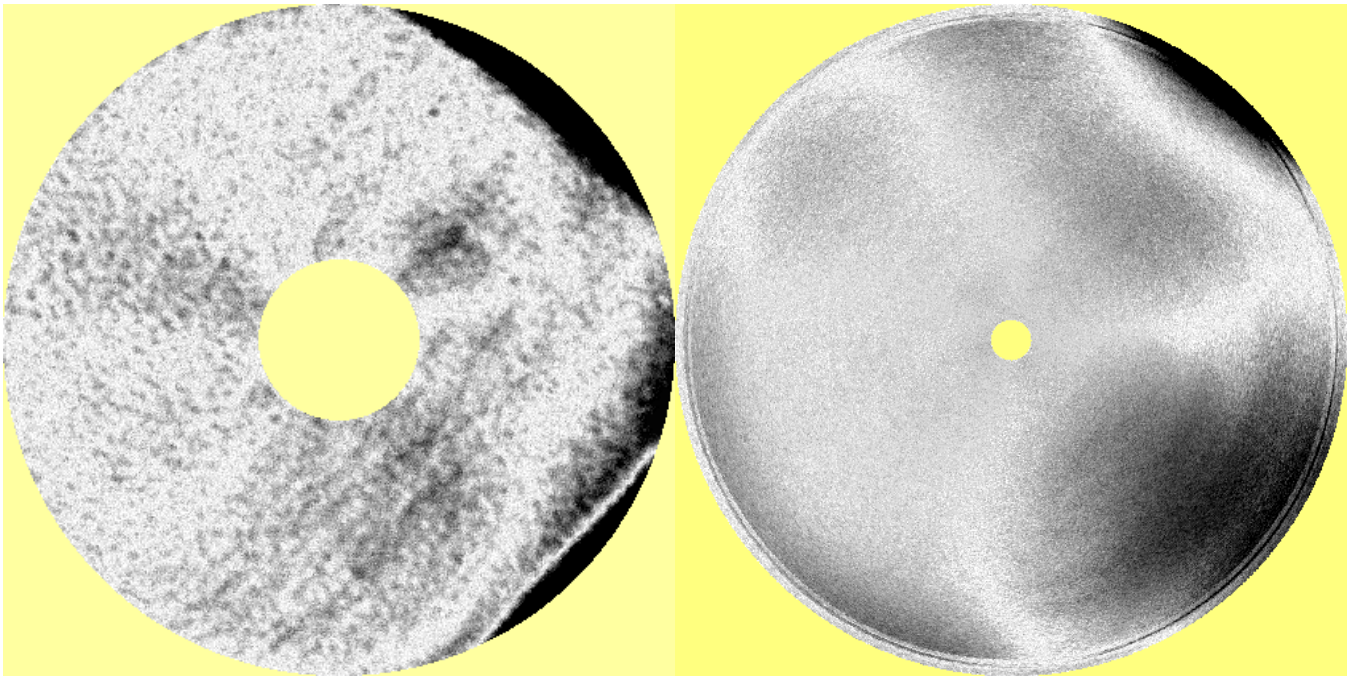
Disc 42 – side 1: DESY (left), SNS/FNAL (right);



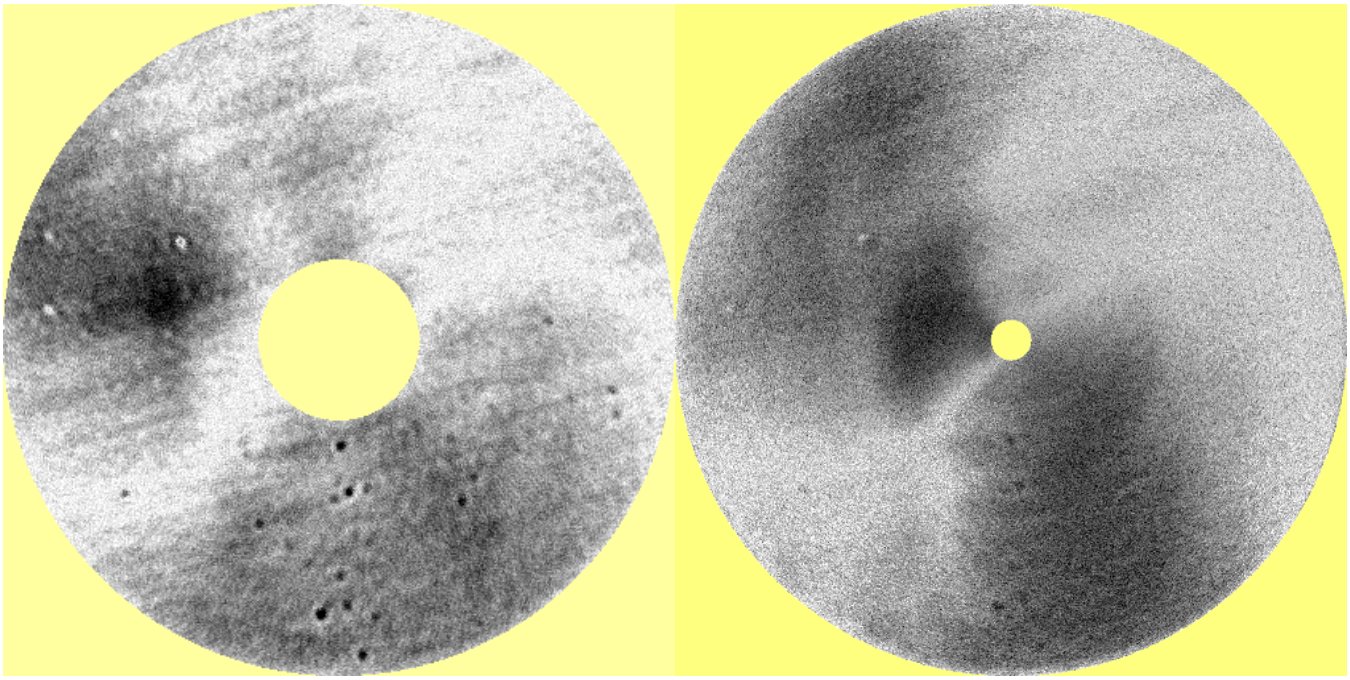
Disc 42 – side 2: DESY (left), SNS/FNAL (right);



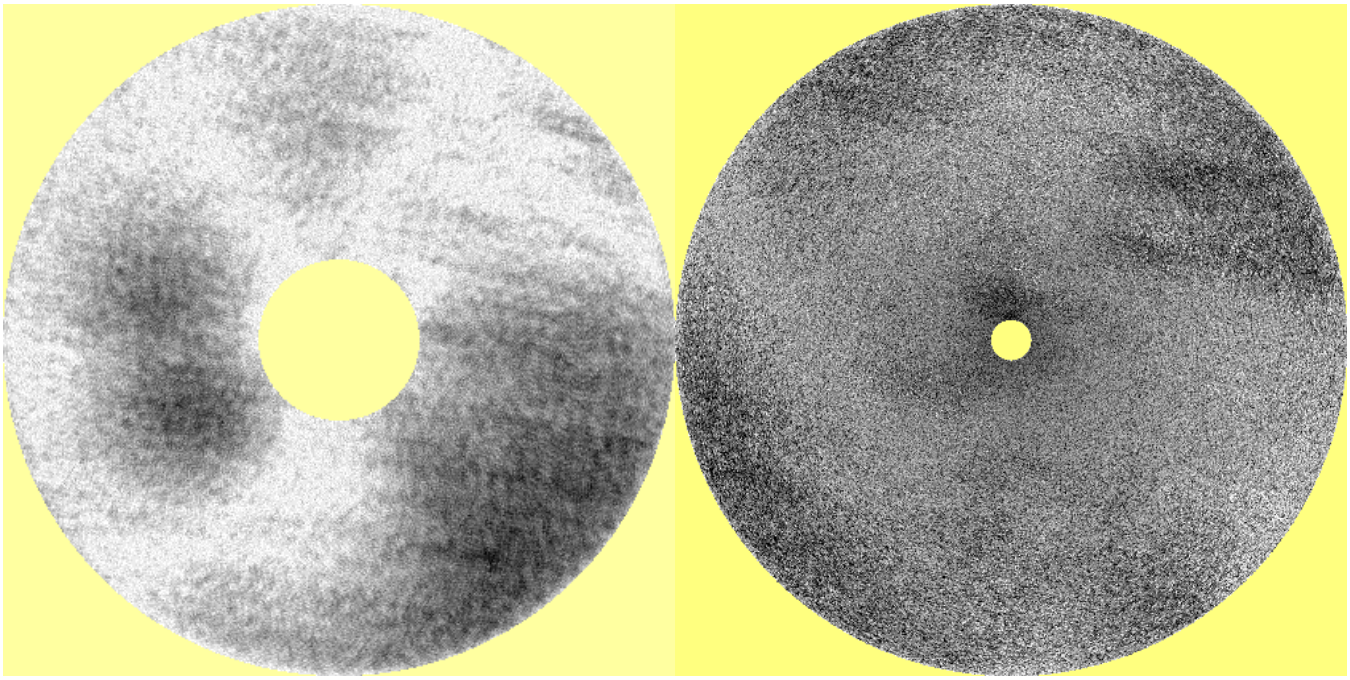
Disc 47 – side 1: DESY (left), SNS/FNAL (right), defects found in DESY scan;



Disc 47 – side 2: DESY (left), SNS/FNAL (right);



Disc 51 – side 1: DESY (left), SNS/FNAL (right), defects found in DESY scan;



Disc 51 – side 2: DESY (left), SNS/FNAL (right);

4 SPECIAL MEASUREMENTS

The eddy current scans discussed here have revealed a particular class of defects in this batch, consisting of holes, which are, in most cases, visible on the surface. Their origin is unknown – they could be etching pits as well as dents inflicted by tooling. The question was raised if this type of defect is sufficiently superficial to disappear during the ~120 μm of surface removal due to the etching steps in the subsequent cavity fabrication procedure.

Figure 5 shows the results of eddy current scans performed with the SNS/FNAL scanner on disc 14-2 before and after removing 175 μm with BCP etching. The plots clearly show a change of appearance of the scan, possibly a result of the increase of surface roughness due to the BCP etching. The change of surface appearance can also be seen in Figure 6, which shows a similar comparison for disc 14 – side 1 (which had not visible defects before etching) and Figure 7, which shows a similar comparison for disc 19 – side 2. Also, and this is corroborated by simple visual inspection, most defects are still present after etching. This result indicates that the defects found in some blanks from this batch will not be removed by the subsequent etching steps and that these particular disc-sides should not be used for the inside of the cavities. Since the total surface removed with BCP etching according to the current cavity fabrication procedure is 50 μm less than the 175 μm removed in this test, this test also addressed the possibility of an additional 50 μm pre-etching. More than 50 μm of pre-etching is not permitted since the thickness variations of the discs wil be larger than allowable for welding and deep-drawing (one also needs to include the “natural” thickness variation of the discs of up to 100 μm!).

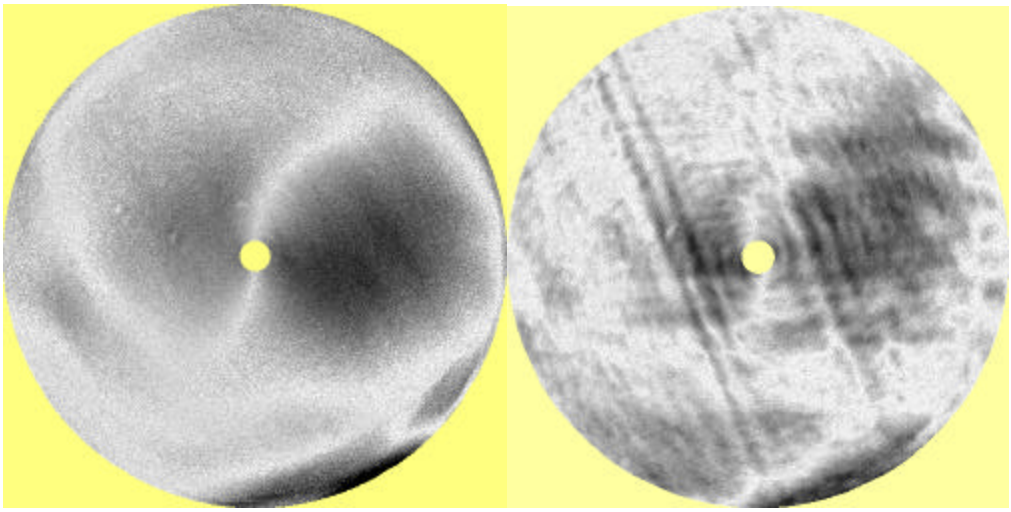


Figure 5: Scan of disc 14/2 before (left) and after (right) 175 μm were removed with BCP etching.

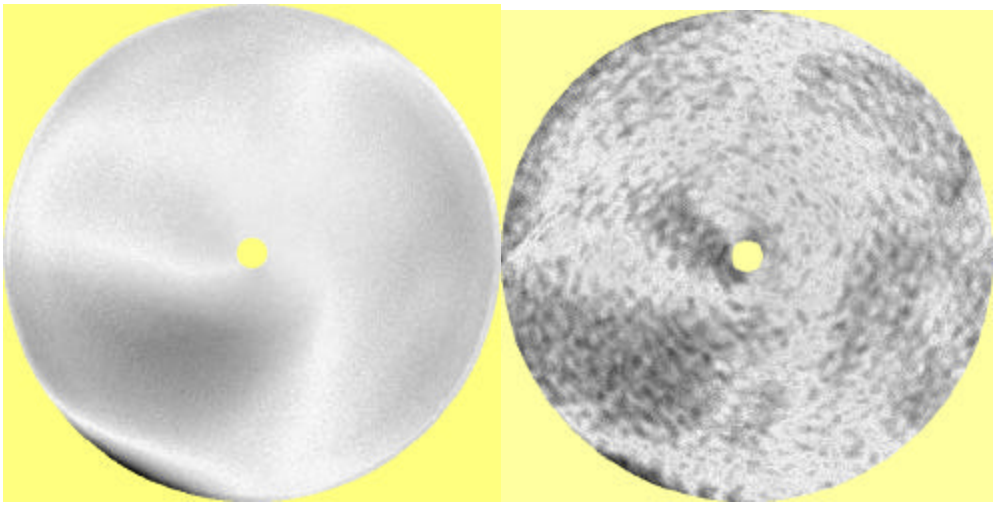


Figure 6: Scan of disc 14/ 1 before (left) and after (right) 175 μm were removed with BCP etching.

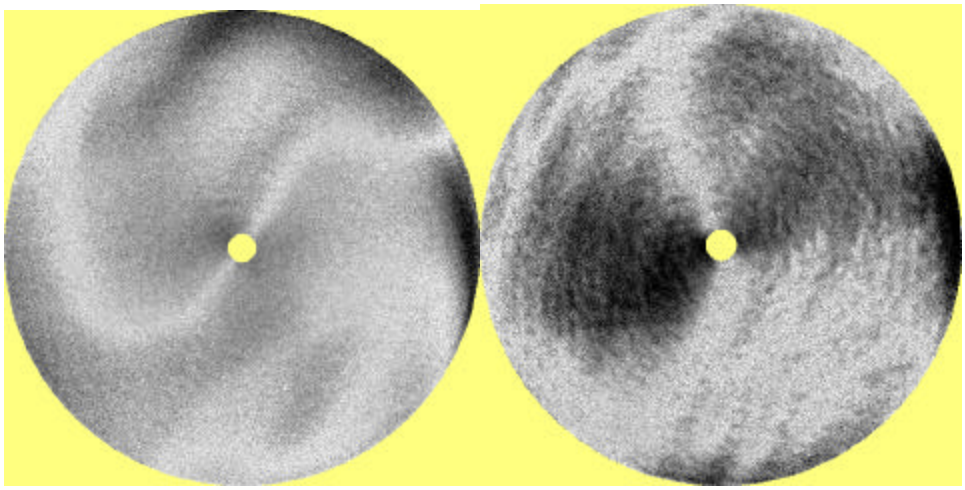


Figure 7: Scan of disc 19/2 before (left) and after (right) 50 μm were removed with BCP etching.

5 SUMMARY

All 27 discs discussed in this report were scanned with the DESY and the SNS/FNAL eddy-current scanners. As previously identified by DESY 11 out of the 27 discs have defects on one side. Most of these defects are visible by the naked eye as dents (pits). The comparison of the DESY and SNS/FNAL scanners has shown that the SNS/FNAL scanner is less sensitive, detecting less than 50% of the defects detected with the DESY scanner.

Tests on disc 14 have revealed that these defects are not removed even after 175 μm of BCP etching. Therefore it is not recommended to use these sides of the discs on the inside of the cavity, even after some pre-etching.

Table 3 summarizes the findings for each of the 27 discs, including the results of a visual inspection of the surface. Table 3 summarizes the defects found on each side. Typically these are scratches, short scratches or dents, and holes / pits of various sizes. The last column in the table suggests which, if any, of the sides can be used on the inside of a cavity. If a side of a cavity is indicated in green no defect could be detected. A red **NO** label indicates that this disc should not be used in a cavity under any circumstance. The pink **NO(S1,2)** labels were given to discs which shouldn't be used. The side indicated is the side with the better quality. Since the defects in these discs are mostly shallow surface scratches, the attempt could be made to render them usable e.g. with a light etch.

According to the here presented classification 14 discs can be used immediately in a cavity. The other four discs needed for the 3rd harmonic cavity could be obtained from the set of eleven discs with the NO(S1,2) label. We proceeded with BCP etching eight discs from this category by 50 μm. These discs are labeled with a * symbol in Table 3. All eight discs were indeed repaired in this process and can now also be used in the fabrication of the 2nd prototype of the 3rd harmonic cavity. A special etching fixture was prepared to pre-etch the discs. It is shown in Figure 8. Three additional discs (19, 42, 51) listed in Table 3 can also be repaired by pre-etching, should the need arise.

Table 3: Summary table for blanks for 2nd 3rd-harmonic prototype cavity. (ECS) stands for eddy-current scan; (VI) stands for visual inspection; Red text: discs (sides) with defects as identified by A. Brinkmann / DESY. Green side label stands for sides of discs that can be used on the inside of the cavity. Red NO: discs that cannot be used in cavities under any circumstances; Pink NO: Discs that should not be but can be used if unavoidable;*Repaired discs after 50 mm pre-etching;

#	SIDE 1	SIDE 2	ADD. COMMENT	RECOM
1	OK	defect (ECS), scratch (VI)	S2 scratched from scanning	S1
2	OK	scratch (VI)	-	S1
3	OK	scratch (VI)	-	S1
4	dent (VI) ??	OK	S2 scratched from scanning	S1
5	OK	pit (VI)	-	S1
6	dent (VI)	OK	-	S2
7	OK	OK	-	S1
8	defects (ECS), pits & scratches from scan (VI)	scratches (VI)	S1 scratches removed with ~50 µm etch	S1*
9	pit OR (VI)	deep scratches (VI)	-	S1
10	dent & speck (VI)	dent OR (VI)	-	S2
11	pit (VI)	scratch (VI)	S2 scratch removed with ~50 µm etch	S2*
12	scratches (VI)	defect (ECS), scratches (VI)	S2 scratched from scanning, S1 scratches removed ~50 µm etch	S1*
13	large pit (VI)	scratches (VI)	S2 scratch removed with ~50 µm etch	S2*
14	dent (VI)	defects (ECS), pits (VI)	not usable after 175 µm etch	NO
15	speck (VI)	scratch (VI)	-	S1
17	defects (ECS), pits (VI)	scratches (VI)	S1 scratched from scanning, S2 scratches removed w ~50 µm etch	S2*
19	long (shallow?) scratch (VI)	defect(ECS),pits&scratches (VI)	disc etched 50 µm	NO(S1)
20	scratches (VI)	specks (VI)	-	S2
21	pits&scratches (VI)	speck&scratch (VI)	S1 scratches removed ~50 µm etch	S1*
22	-	defects (ECS), pits (VI)	**"calibration disc"**	NO
24	deep long scratch (VI)	scratches & pit (MR?) (VI)	S2 scratches removed with ~50 µm etch	S2*
27	small scratch, weak scan marks	defects(ECS), pits&scratches(VI)	-	S1
32	dent (VI)	defects(ECS), pits&scratches(VI)	S1 scratches removed with ~50 µm etch	S1*
33	Pits and scratches (VI)	shallow scratch	0.0035"bumpOR, very irreg. EDMcut	S2
42	pit (VI)	shallow pit & scratches (VI)	-	NO(S1)
47	defect (ECS), pits&scratches (VI)	OK	-	S2
51	defects (ECS) pits&scratches (VI)	scratch MR&weak scanmarks(VI)	-	NO(S2)

Figure 8: 3rd harmonic blank pre-etching fixture designed and manufactured by D. Assel.